Bulletin 21:

THE EFFECT OF PUMPED-STORAGE RESERVOIR OPERATION ON BIOLOGICAL PRODUCTIVITY AND WATER QUALITY

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PREFACE

With the increased utilization of our water resources by a growing population, intelligent management of these resources, giving full consideration to all the relevant factors, becomes essential. Pumped-storage hydroelectric projects have been developed giving primary emphasis to the factors which relate to the generation of electricity. These projects can also provide a means of reducing stream pollution effects through stream flow augmentation and by lessening the effects of thermal stratification.

This study was undertaken in order to establish the basis for assessing the effect of pumped-storage operation on reservoir water quality. Certain physical, chemical, and biological factors were examined to provide a baseline for subsequent studies. Primary productivity estimates closely approximate photosynthesis in the reservoir and provide a means of appraising the reservoir's capacity to support and sustain aquatic life. These estimates show Smith Mountain Reservoir to be a moderately productive body of water with a variety of aquatic organisms that are characteristic of the transition from a stream to a lake environment. Physical and chemical data further characterize the factors that influence the aquatic life within the environment. Part of the reservoir is under the influence of detrimental pollution and increases in the primary production values illustrate the effect of these effluents. The pollution restricts the kinds of organisms in the area of the reservoir affected, but the numerical number of those remaining increase

This investigation has shown that the recycling of water during pumped-storage operation does disrupt thermal stratification (which results from water density differences due to temperature) in the Smith Mountain impoundment, although the dimensions of the impoundment's basin tend to localize the recycling effect. The poor quality of some of the water being recycled further reduces beneficial effects. In terms of dissolved oxygen, coliform bacteria, and nutrients in solution, the quality of the water available for recycling will be a large determinent as to how much pumped-storage operation will enhance water quality.

In the past, little consideration has been given to the resulting effect of site location, dam design, and reservoir management of water quality within the future impoundment. Experience has shown that newly created reservoirs are often biologically unproductive. Eutrophic conditions sometimes develop from discharges of domestic and industrial pollution.

The ever increasing demand for electric power coupled with the economic advantage provided by nuclear power installation will likely increase the number of pumped-storage installations. Paralleling this electric demand is a new public awareness of the ecological considerations of alterations of natural systems. This study on Smith Mountain Reservoir provides a basis for future work and comparisons with other pumped-storage reservoir operations. It is hoped that this study will stimulate greater consideration of the limnological implications of such impoundments on water quality as site investigations are carried out and aid in the planning and management of the generating installation. The placement of the penstocks and provision for monitoring the water available for recycling are two factors in the planning and management of a power installation that can significantly modify some of the limnological conditions and assist in improving water quality in the holding reservoir. Other factors will become evident as additional research is conducted in this very important area of water resource management.

William R. Walker
Director

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INTRODUCTION

Pumped-storage, hydroelectric power plants are designed to increase the power system's load factor and to permit the system to accommodate daily, weekly, and seasonal peak capacity requirements at lower costs. The power plants have been in operation since 1908, and have complied an impressive history of development and dependable operation. Nearly 90 pumped-storage plants are now in operation throughout the world. In the United States, eight pumped-storage plants are operating, and more are planned or contemplated (Harza, 1962). A number of the older plants have utilized separate pumps to refill the holding pool. Recent improvements in the design of reversible pump turbines have increased the economic feasibility of pumped-storage plant construction.

In addition to providing power economically during peak demand periods and increasing the load factor, pumped-storage projects have been proposed to supplement flood control impoundments by balancing seasonal power requirements with periods of high water flow. During periods of low flow or in areas where stream flow fluctuates, pumped-storage impoundments can be used to augment stream flow and to improve water quality (Velz, et. al.; 1966). This is achieved through the control and modification of the discharge pattern. As water use increases and as the load imposed upon streams by detrimental effluents becomes greater, the possibility of flow augmentation by use of pumped-storage impoundments takes on added importance. The increased cost of pumped-storage reservoirs may be well worth the investment if we can prevent further deterioration of our natural waters.

Operation of a pumped-storage power project involves the transfer of water from one impoundment to another. During periods of peak power demand, water is drawn from an upper reservoir to a lower reservoir and electrical power is produced. As power demands decrease, the excess power in the system is used to pump water from the lower reservoir back into the upper reservoir or holding pool in order to maintain a maximum head of water. Such a schedule of operation enables a power company to meet peak power demands more easily and increases the system's load factor. Recycling of water back into the upper impoundment usually takes place at night with sustained pumping being carried out on weekends as the pool level requires.

Most of the pumped-storage plants now in operation do not have large upper reservoirs or holding pools which remain filled during peaking periods. In these plants, the upper holding pool is often almost completely drained during peaking periods and is refilled during periods of low demand. Clearly, these impoundments do not simulate the lacustrine conditions that occur in other reservoirs. The operation of a pumped-storage system in which the upper impoundment possesses a large volume and hence maintains limnetic conditions along with the recycling of a large quantity of water in a relatively short period of time makes these pumped-storage projects of limnological interest. The turbulence created during the recycling process can disrupt the untoward effects of thermal stratification and recirculate needed nutrients to plants and animals.

Several attempts to alleviate the detrimental effects of summer stratification and stagnation have been made by limnologists (Hooper, et. al., 1952; Irwin, et. al., 1966). These attempts have met with varying degrees of success. Unless the body of water has a relatively small (circa 5 acres) surface area, stratification is usually re-established rapidly. Since Smith Mountain Reservoir has a large surface area (just over 22,000 acres) and the recycling operation in on a regular schedule, the upper impoundment affords an opportunity to examine the physical and chemical features of the body of water and to study the effects of the recirculated water on stratification and primary production in the impoundment. Since the impoundment was new when this study began, some baselines for the limnological features of the body of water had to be established before primary production estimates could be interpreted.

Smith Mountain Reservoir, Virginia is the upper impoundment of a two-reservoir, pumped-storage hydrogeneration system which has been constructed by he Appalachian Power Company. Details of the project design and equipment have been reviewed by Hroncich and Mullarkey (1962). The upper reservoir reached its normal operating level in February. 1965. Morphometric data pertaining to the limnological aspects of Smith Mountain Lake are given in Table 1.

The objectives of this study were to determine the effects of the operation of the Smith Mountain power plant on the primary productivity of the upper impoundment and to ascertain what effect the quantity of recycled water might have on the limnological characteristics of the upper impoundment.

TABLE 1. Summary of Morphometric Data on Smith Mountain Lake, Virginia

Area	22,058.4 acres
Maximum Depth	200 feet
Mean Depth	57.1 feet
Volume	1,254,671.4 acre-feet
Length	
Roanoke River arm	40 miles
Blackwater River arm	20 miles
Shoreline length	500 miles
Drainage area	1,020 square miles
Maximum pool elevation	795 feet above sea level
Normal drawdown pool elevation	793 feet above sea level
Maximum drawdown pool elevation	787 feet above sea level
Normal usable storage	150,000 acre-feet

METHODS

Four stations were established in Smith Mountain Lake to determine the effects of recycling on primary production (Fig. 1). Station 1 was located on the Blackwater River arm, Station 2 on the Roanoke River arm, Station 3 at the confluence of the two arms, and Station 4 situated at the mouth of the gorge leading to Smith Mountain Dam. Each station was selected to contribute information about effluents and recycling. Since the Blackwater River flows through farmland, Station 1 was relatively free from industrial and domestic effluents and served to monitor production and water quality in the reservoir. Station 2 and 3 were chosen to show production and water quality under the varying influence of urban effluents. Station 4 was established to follow changes in primary production that might be influenced by the recycling of water during scheduled operations at the dam.

Estimates of primary productivity were made using the techniques described by Goldman (1961) and, with some modifications, the techniques of Saunders et. al., 1962. A number of modifications of the Carbon-14 methods have been used since the introduction of the technique by Steemann-Nielsen (1951, 1952). Five microcuries of $NaH^{14}CO_3$ were added to 300 ml of lake water which had been collected at 1 meter depth intervals. Samples were suspended in the lake at the depth from which the sample had been collected for a period of 6-8 hours. Bottles were removed from the lake, placed in a light-proof chamber, and returned to the laboratory for processing. Samples were filtered through a 47 mm HA 0.45 μ Millipore filter. After the residue had been rinsed with 0.003N HCl to remove ^{14}C which had precipitated or become bound as mono-carbonates, the filters were rinsed with 10% formalin and affixed to planchets and then dried. Activity of the sample was determined with a Beckman Lowbeta II gas-flow counter. The efficiency of the counter was determined each time counts were made by a standard planchet of known activity. After counts were made, sample activity was then converted to mgC/ unit area/day, using the methods and tables of Saunders et. al., 1962. Modifications of the method used in this study are given by Simmons (1968).

Water temperatures and dissolved oxygen concentrations were obtained with a Yellow Springs Instrument (YSI) Model 51 thermister-oxygen probe and a Wallace & Tiernan 200-foot Bathythermograph. Oxygen concentrations were confirmed routinely using the Alsterberg modification of the Winkler method (Welch, 1948; Standard Methods, 12th ed., p. 406). Total alkalinity

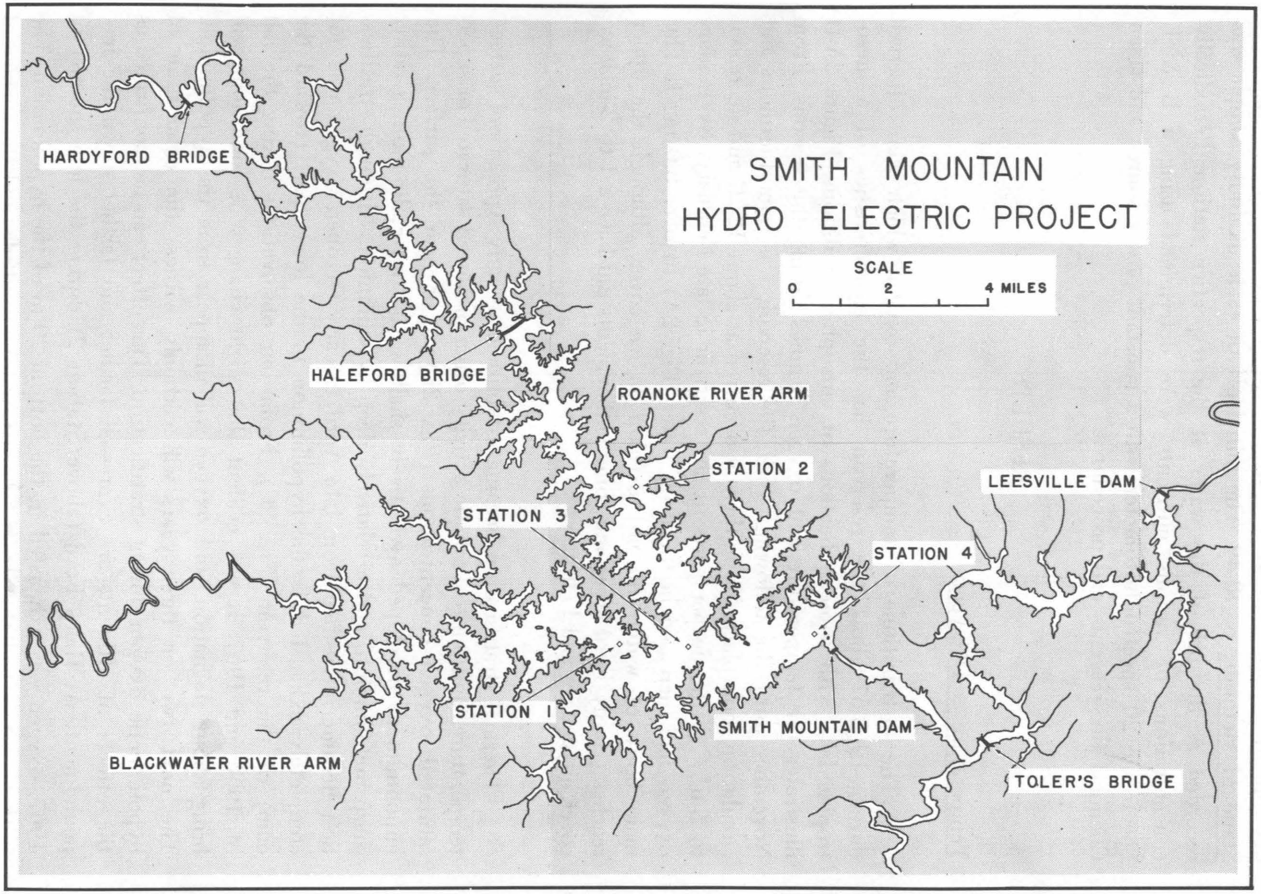


Figure 1. Smith Mountain and Leesville Reservoirs. North is at the top of the figure and each sampling station location is designated by an arrow.

determinations were made by the potentiometric method outlined in Standard Methods, p. 48-49. The initial pH of each alkalinity sample was recorded as the pH of the water at the respective station. Periodically concentrations of various nutrients were determined using a B & L Spectronic 20 spectrophotometer with a constant power source and Hach Chemical Co. reagents and procedures.

RESULTS

Temperature and Oxygen

The distributions of temperature and oxygen which were observed during 1965-67 show the reservoir has the characteristics of a mesotrophic lake with some indications of eutrophic conditions. Figure 2A-D illustrates the temperature and oxygen regimes during the seasons. From November until the following April, the reservoir was homothermous and circulation took place. Homothermy occurred at about 12° C and decreased to 5-6° C in the deeper parts of the reservoir in late February. By January oxygen had increased in the deep water (Fig. 2A) to over 8.0 mg/1. The main body of water did not develop an ice cover, although the upper reaches (Hardy Ford area) and some embayments did have a 1-to 2-inch ice cover in January and February.

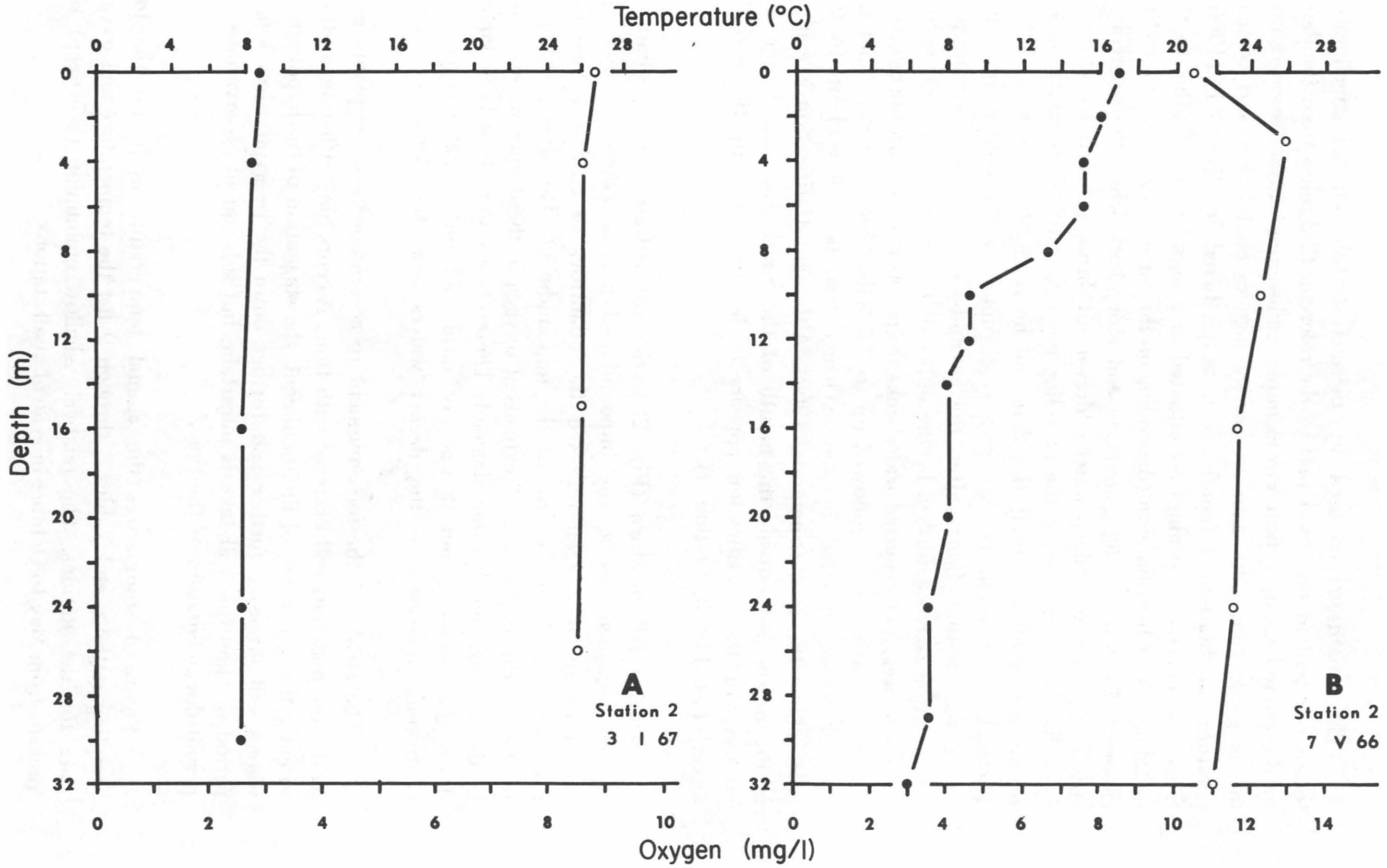
Thermal stratification became established in early April. Cool surface temperatures and photosynthetic activity often produced saturated or supersaturated oxygen concentrations (Fig. 2B) at or near the surface. The impoundment developed a relatively shallow (6-8 m) epilimnion, a rather sharp metalimnion, and a relatively deep hypolimnion. Although stratification became intensified from late April to early October, oxygen was not completely exhausted in the hypolimnion in the lower part (toward the dam) of the reservoir (Fig. 2C). From our observations during the fall of 1966 and 1967, it was evident that slight changes in conditions will bring about stagnation, and oxygen will disappear from the hypolimnion. The next two or three years will certainly witness the exhaustion of hypolimnetic oxygen during stratification. This effect can be confirmed as the effects of effluents are expressed farther and farther down the impoundment. At Hales Ford (above Station 2) during the late summer of 1967, oxygen was exhausted in the bottom 20 m of the hypolimnion. The bottom waters had the strong odor of hydrogen sulfide, and the surface of the bottom sediments was black and odorous, typical of a reducing milieu.

The conditions imposed by thermal stratification are ameliorated to some extent in the lower part of the reservoir (2-3 miles from the dam) by the pump-back operation. For example, mid-summer surface temperatures in the gorge above the dam are several degrees cooler than surface temperatures at Station 3 (confluence), as predicted by Reynolds (1966). Since the penstock openings are situated at a depth corresponding to the metalimnion or hypolimnion (depending on the turbines used), an interesting situation develops during generation and pump-back when the reservoir is stratified. The colder, deep water is drawn out during generation and enters Leesville Reservoir. During the recycling process, water temperatures in the region immediately behind the dam can be reduced as much as 10° C. Thermal stratification in that area is disrupted as the colder water fills the gorge. Within hours after the pump-back operation has stopped, stratification is re-established by the influx of the warm surface waters into the gorge area. The recycled water sinks deeper as it moves up the reservoir. The water mass can be followed up to 3.5 miles above the dam, and the internal seiche initiated by the exchange, can be followed up to 6.5 miles above the dam (Simmons, 1968). Although stratification is evident in the region just outside the mouth of the Smith Mountain Gorge, the intensity of the stratification appears to be diminished by the periodic mixing (see Fig. 3, Station 4).

During fall overturn (Fig. 2D), the concentration of hypolimnetic oxygen remained low as the impoundment became homothermous. The concentration of oxygen reflected the quantities of oxidizable materials that enter the Roanoke arm of the impoundment. The shallower, upper reaches of the impoundment exhausted oxygen in the deeper waters early in the summer and became stagnant. These effects were seen later farther down the reservoir, and it was not until mid-winter that oxygen concentrations increased in the deeper waters near the dam. (Fig. 2A).

The ability of the impoundment to accommodate large quantities of oxidizable materials will decrease with time. As enriching effluents continue to enter the upper end of impoundment, the stagnation of the hypolimnetic waters will intensify further and further down the reservoir. How long a period of time this will take is uncertain, but subsequent observations will permit documentation of the time.

Figure 3 summarizes the annual temperature cycle for the four sampling stations, and Tables 2 through 9 list the temperature and oxygen data for the stations. The relatively shallow epilimnion (5-7 deep) that prevails from May to October in evident at all stations.


Temperature (°C)
Depth (m)
Oxygen (mg/l)
A
Station 2
3 I 67
B
Station 2
7 V 66

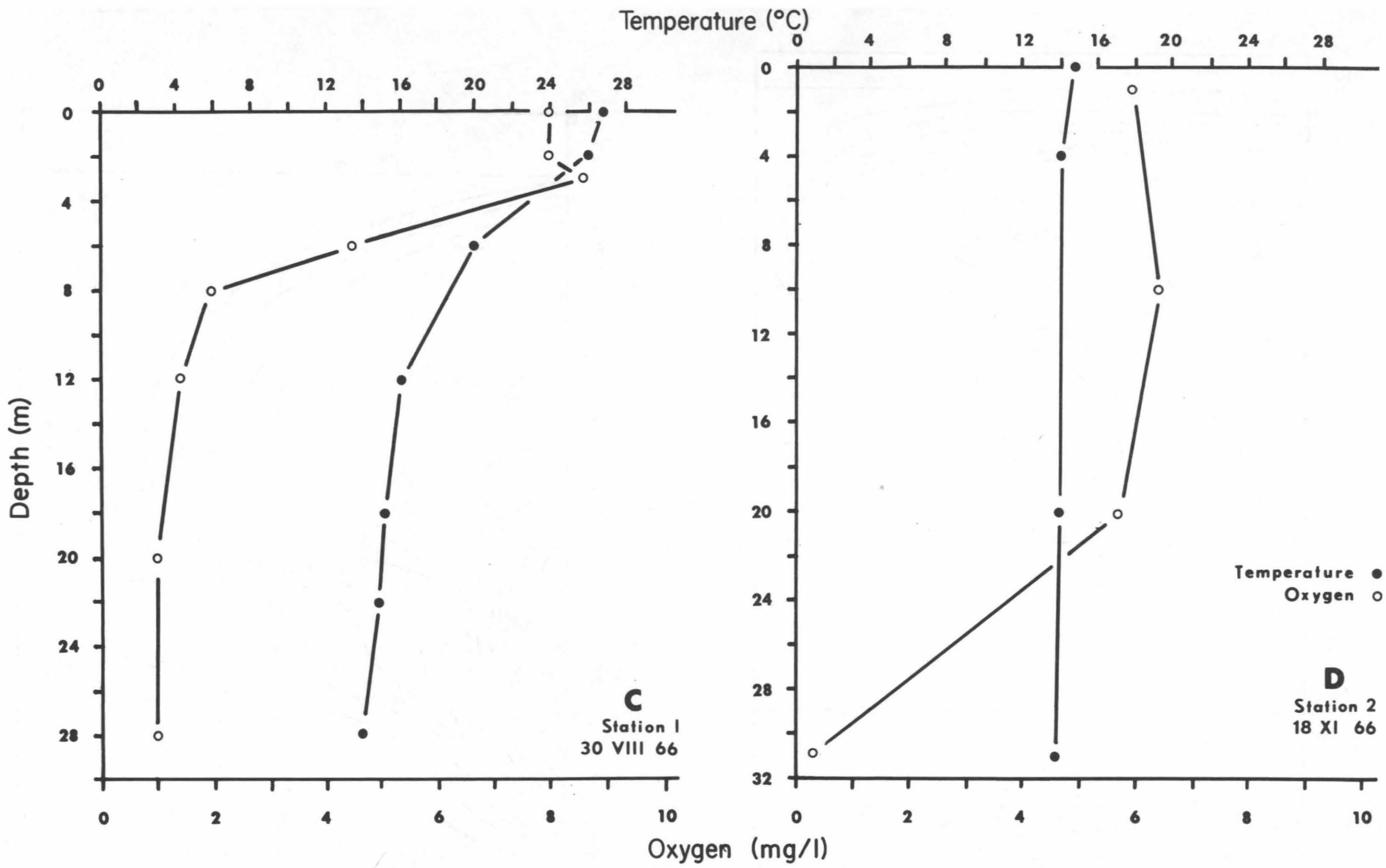
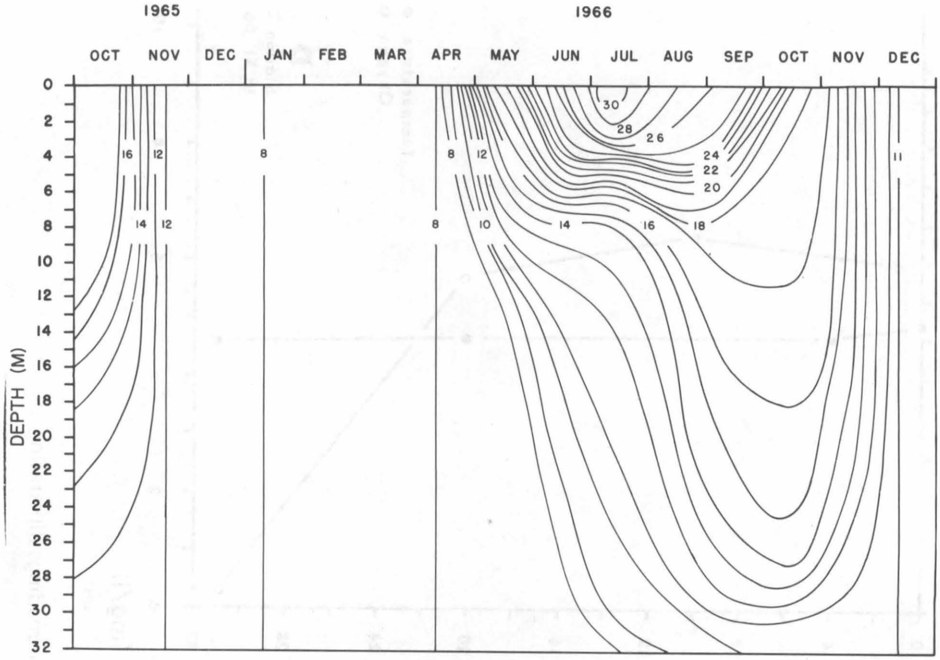
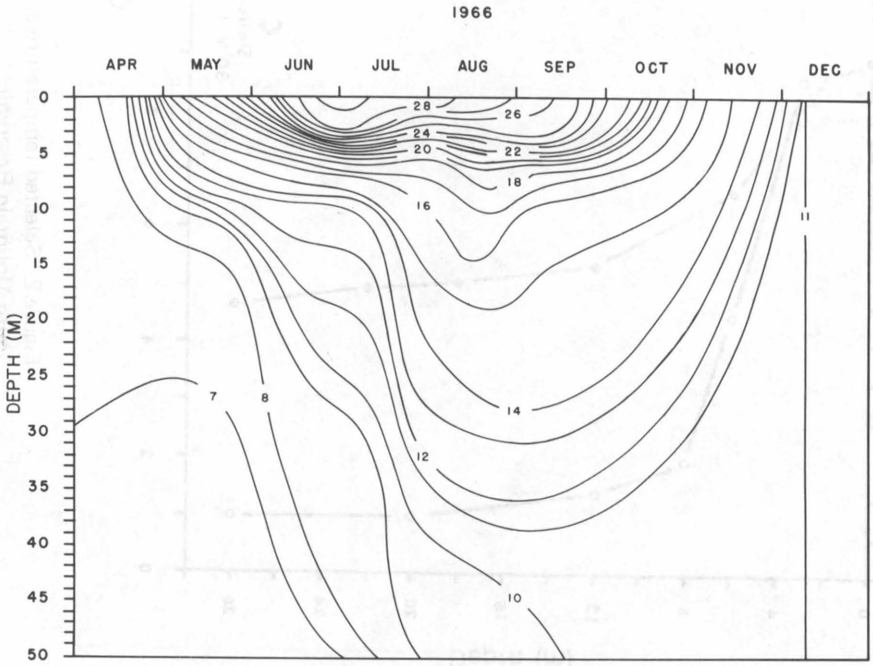


Figure 2. Selected temperature and oxygen readings illustrating conditions in Smith Mountain Reservoir.



STATION 1



STATION 3

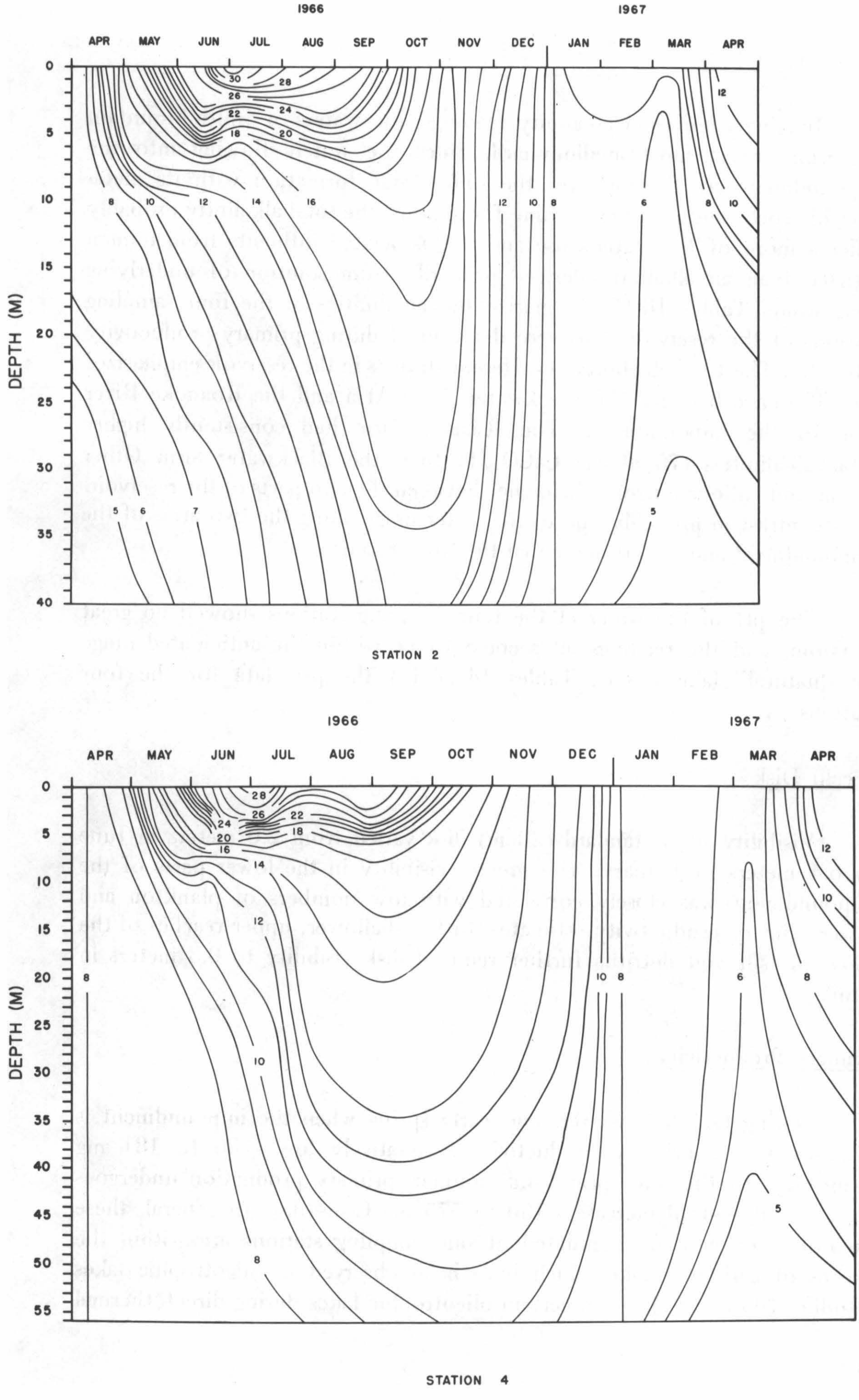


Figure 3. Temperature distributions in Smith Mountain Reservoir at the four sampling stations. Isopleths are in degrees Celsius.

Alkalinity and pH

Judging from total alkalinity readings, the waters of Smith Mountain Reservoir are at most medium-hard. Since the waters flowing into the impoundment are flowing over the Blue Ridge formation with its metamorphic rocks and other crystalline formations, the total alkalinity probably reflects more of the water's use and the associated influents from human activity than an alkalinity derived primarily from solution of underlying rock strata. Tables 10-13 summarize the alkalinities of the four sampling stations of the reservoir that were determined during primary productivity estimates. The total alkalinity at different stations in the reservoir emphasizes the difference between the Blackwater River Arm and the Roanoke River Arm of the impoundment. The Roanoke arm had consistently higher total alkalinities (75-90 mg $CaCO_3/1$) than the Blackwater arm. Other anions and cations mirror a difference between the two parts of the reservoir. This contrast in probably due to the water usage along the two arms of the impoundment and the effluents that the River receives.

The pH of the water at the four sampling stations showed no great variation, and the readings all seemed to be within the anticipated range for "natural" lake waters. Tables 14-17 list the pH data for the four stations.

Secchi Disk

Visibility of a standard (20cm) disk varied from 2.0 meters in June to 6.4 meters in January. The greater visibility in the lower parts of the impoundment was closely correlated with low numbers of plankton and lower primary productivity estimates. In the shallower, upper reaches of the reservoir, silt and detritus further reduced disk visibility to 0.3 meters in June.

Primary Productivity

During late fall, winter, and early spring when the impoundment is homothermous, primary productivity is relatively low - 36 to 181 mg $C/m^2/day$. In the late spring and summer, primary production undergoes a two-to three-fold increase - 150 to 575 mg $C/m^2/day$. In general, these quantities of carbon assimilated at our sampling stations are within the ranges of carbon uptake which have been observed in oligotrophic lakes (Rodhe, 1958, 1967). As in certain oligotrophic lakes during direct, thermal

TABLE 2. Water Temperature in °C at various depths at Station 1 (Blackwater River arm), Smith Mountain Reservoir

	1965		1966									1967	
Depth m	Oct 22	Nov 20	Jan 8	Apr 8	May 7	Jun 17	Jul 2	Aug 30	Oct 17	Nov 18	Dec 8	Feb 3	Mar 9
0	17.2	12.1	8.0	8.0	18.0	26.0	30.5	26.8	19.0	14.5	11.0	7.3	6.3
1	17.1	12.0	8.0	8.0	17.0	25.0	30.0	26.0	18.5	14.0	11.0	7.3	6.3
2	17.1	12.0	8.0	8.0	15.5	25.0	29.0	26.0	18.0	14.0	11.0	7.0	6.0
3	17.1	12.0	8.0	8.0	15.0	25.0	27.0	25.5	18.0	14.0	11.0	7.0	6.0
4	17.1	12.0	8.0	8.0	15.0	23.0	23.0	24.8	18.0	14.0	11.0	7.0	6.0
5	17.1	12.0	8.0	8.0	15.0	20.0	20.0	22.0	18.0	14.0	11.0	7.0	6.0
6	17.1	12.0	8.0	8.0	13.0	18.0	17.0	20.0	18.0	14.0	11.0	7.0	6.0
7	17.1	12.0	8.0	8.0	12.5	15.5	15.5	19.0	18.0	14.0	11.0	7.0	6.0
8	17.0	12.0	8.0	8.0	10.5	14.0	14.0	17.5	18.0	14.0	11.0	7.0	6.0
9	17.0	12.0	8.0	8.0	10.0	13.0	13.5	17.0	18.0	14.0	11.0	7.0	6.0
10	17.0	12.0	8.0	8.0	9.0	13.0	13.0	16.5	17.5	14.0	11.0	7.0	6.0
11	16.1	12.0	8.0	8.0	8.0	12.0	13.0	16.2	17.0	14.0	11.0	7.0	
12	16.0	12.0	8.0	8.0	8.0	12.0	12.5	16.0	17.0	14.0	11.0	7.0	5.7
13	15.2	12.0	8.0	8.0	8.0	11.5	12.0	16.0	17.0	14.0	11.0	7.0	5.7
14	14.5	12.0	8.0	8.0	8.0	11.0	12.0	15.5	16.5	14.0	11.0	7.0	5.7
15	14.2	12.0	8.0	8.0	8.0	11.0	12.0	15.5	16.5	13.9	10.5	7.0	5.7
16	14.1	12.0	8.0	8.0	8.0	10.5	12.0	15.1	16.2	13.9	10.5	7.0	5.7
17	13.5	12.0	8.0	8.0	8.0	10.0	11.5	15.0	16.2	13.9	10.5	7.0	5.7
18	13.5	12.0		8.0	7.5	10.0	11.5	15.0	16.0	13.9	10.2	7.0	5.7
19	13.5	12.0				10.0	11.0	15.0	16.0	13.9			
20	13.0	12.0				10.0	11.0	15.0	16.0	13.8		6.7	5.5
21	13.0	12.0				9.5	11.0	15.0	16.0	13.8		6.7	5.5
22	13.0	12.0				9.0	10.5	14.8	16.0	13.8		6.7	5.5
23	13.0	12.0				9.0	10.5	14.5	16.0	13.8		6.7	5.5
24	12.5	12.0					10.0	14.5	16.0	13.8		6.7	5.5
25	12.2	12.0					10.0	14.5	16.0	13.8		6.7	5.5
26	12.0						10.0	14.1	16.0	13.8		6.7	5.5
27	12.0						9.5	14.0	16.0	13.8		6.7	5.5
28	11.9						9.5	14.0	16.0	13.5		6.7	5.5
29	11.5						9.0		16.0				5.5
30	11.2						9.0		15.2			6.5	5.5
31	11.0						N.B.*					6.5	5.5
32	11.0						N.B.					6.5	5.5

N.B., "No Bottom," means that the temperature probe did not reach the lake bottom.

TABLE 3. Water temperature in °C at various depths at Station 2 (Roanoke River arm), Smith Mountain Reservoir

Depth m	1966 Apr 8	May 7	Jun 17	Jul 2	Aug 30	Oct 17	Nov 18	Nov 26	Dec 8	1967 Jan 3	Feb 3	Mar 9
0	8.0	17.0	27.0	31.5	27.5	19.0	14.5	14.0	11.2	8.2	7.7	7.0
1	8.5	17.0	26.0	30.0	26.5	18.5	14.1	13.5	11.0	8.0		
2	8.5	16.0	25.5	26.5	26.0	18.5	14.0	13.5	11.0	8.0	7.3	6.0
3	8.5	15.0	25.5	23.5	25.5	18.2	14.0	13.1	11.0	8.0		6.0
4	8.5	15.0	23.0	20.0	24.5	18.0	14.0	13.0	11.0	8.0	7.0	6.0
5	8.8	15.0	21.5	18.0	22.0	18.0	14.0	13.0	11.0	7.9	7.0	6.0
6	8.8	15.0	17.0	15.5	20.0	18.0	14.0	13.0	11.0	7.9	7.0	6.0
7	8.8	13.5	16.0	14.0	18.0	18.0	14.0	13.0	11.0	7.9	7.0	
8	8.8	13.5	13.5	14.0	17.2	18.0	14.0	13.0	11.0	7.9	7.0	5.7
9	8.8	10.0	13.0	13.5	16.5	18.0	14.0	13.0	11.0	7.9	7.0	5.7
10	8.8	9.0	12.0	13.0	16.5	17.5	14.0	13.0	11.0	7.9	7.0	5.7
11	8.8	9.0	11.5	13.0	16.0	17.0	14.0	13.0	11.0	7.9	7.0	5.7
12	8.8	9.0	11.5	12.5	16.0	17.0	14.0	13.0	11.0	7.9	7.0	5.7
13	8.8	8.0	11.0	12.5	15.5	17.0	14.0	13.0	11.0	7.9		5.7
14	8.0	8.0	11.0	12.0	15.5	16.5	14.0	13.0	11.0	7.9	6.7	5.7
15	8.0	8.0	10.5	12.0	15.5	16.5	14.0	13.0	11.0	7.9		
16	8.0	8.0	10.5	11.5	15.0	16.2	14.0	13.0	11.0	7.9	6.5	5.5
17	8.0	8.0	10.0	11.5	15.0	16.2	14.0	13.0	11.0	7.9	6.5	5.5
18	8.0	8.0	10.0	11.0	15.0	16.0	14.0	13.0	11.0	7.9	6.5	5.5
19	7.0	8.0	10.0	11.0	15.0	16.0	14.0	13.0	11.0	7.9	6.5	5.5
20	6.5	8.0	9.5	11.0	15.0	16.0	14.0	13.0	10.8	7.9	6.5	5.5
21	6.0	7.5	9.0	11.0	14.8	16.0	14.0	13.0	10.8	7.8	6.5	5.5
22	6.0	7.5	9.0	10.5	14.8	16.0	14.0	13.0	10.8	7.8	6.5	5.5
23	6.0	7.0	9.0	10.5		16.0	14.0	13.0	10.8	7.8	6.5	5.5
24	5.5	7.0	9.0			16.0	14.0	13.0	10.8	7.8	6.5	5.5
25	5.0	7.0	8.5			16.0	13.9	12.9	10.5	7.8	6.5	5.5
26	5.0	7.0	8.5			16.0	13.9	12.9	10.5	7.8	6.5	5.5
27		7.0	8.0			16.0	13.9	12.9	10.5	7.8	6.5	5.5
28		7.0	8.0			16.0	13.9	12.9	10.5	7.8	6.5	5.5
29		7.0	8.0			16.0	13.9		10.5	7.8	6.5	5.5
30		6.5	8.0			15.2	13.9		10.5	7.8	6.5	5.5
31		6.0	N.B.			N.B.	13.9		10.5	7.8		5.5
32		N.B.					13.9		10.5		6.3	5.5
33							13.9		10.5		6.3	
34									10.5		6.3	5.3
35									10.5		6.3	
36									10.2		6.3	5.0

N.B., "No Bottom," means that the temperature probe did not reach the lake bottom.

TABLE 4. Water temperature in °C at various depths at Station 3 (confluence of Blackwater and Roanoke Rivers), Smith Mountain Reservoir.

1966

Depth m	Apr 8	Mar 7	Jul 2	Aug 30	Nov 26	Dec 8	(cont.)
0	8.0	18.0	29.0	27.0	14.9	11.1	
1	8.0	17.5	28.5	26.5	13.1	11.0	
2	8.0	16.0	28.5	25.8	13.0	11.0	
3	8.0	15.0	28.0	25.0	13.0	11.0	
4	8.0	15.0	24.0	24.8	13.0	11.0	
5	8.0	15.0	20.0	21.0	13.0	11.0	
6	8.0	14.0	17.5	19.0	13.0	11.0	
7	8.0	12.5	16.0	18.0	13.0	11.0	
8	8.0	12.0	15.0	17.1	13.0	11.0	
9	8.0	10.0	14.0	17.0	13.0	11.0	
10	8.0	9.0	13.0	16.5	13.0	11.0	
11	8.0	9.0	13.0	16.0	13.0	11.0	
12	8.0	8.5	13.0	16.0	13.0	11.0	
13	8.0	8.0	12.5	16.0	13.0	11.0	
14	8.0	8.0	12.0	16.0	13.0	11.0	
15	8.0	8.0	12.0	16.0	13.0	11.0	
16	8.0	8.0	12.0	15.5	13.0	11.0	
17	8.0	8.0	12.0	15.5	13.0	11.0	
18	8.0	8.0	11.5	15.0	13.0	11.0	
19	8.0	8.0	11.0	15.0	13.0	11.0	
20	8.0	8.0	11.0	15.0	12.9	11.0	
21	8.0	8.0	11.0	15.0	12.9	11.0	
22	7.5	7.5	11.0	15.0	12.9	11.0	
23	7.5	7.5	10.5	15.0	12.9	11.0	
24	7.5	7.5	10.5	14.8	12.9	11.0	
25	7.5	7.0	10.0	14.5	12.8	11.0	
26	7.5	7.0	10.0	14.5	12.8	11.0	
27	7.5	7.0	10.0	14.1	12.8	11.0	
28	7.0	7.0	9.5	14.0	12.8	11.0	
29	7.0	7.0	9.0	14.0	12.8	11.0	
30	7.0	7.0	9.0	14.0	12.8	11.0	
31	7.0	N.B.	N.B.	N.B.	N.B.	11.0	
32	7.0					11.0	
33	N.B.					11.0	
34						11.0	
35						11.0	
36						11.0	
37						11.0	
38						11.0	
39						11.0	
40						11.0	
41						11.0	
42						11.0	
43						11.0	
44						11.0	
45						11.0	
46						11.0	
47						11.0	
48						11.0	
49						11.0	
50						11.0	

N.B., "No Bottom," means that the temperature probe did not reach the lake bottom.

TABLE 4. Continued

1967

Depth m	Mar 9	Apr 8	Aug 14
0	7.0	12.5	26.5
1			
2	6.7	12.0	25.5
3			
4	6.3	11.7	25.3
5			
6	6.0	11.3	21.0
7	6.0		
8	6.0	10.5	17.0
9	6.0		
10	6.0	9.5	15.0
11			
12	5.7	8.0	14.3
13	5.7		
14	5.7	7.5	13.3
15	5.7		
16	5.7	7.3	13.0
17	5.7		
18	5.7	7.0	12.5
19	5.7	7.0	
20	5.7	7.0	12.0
21	5.7		
22	5.7	6.7	11.5
23		6.7	
24	5.5	6.7	11.3
25	5.5		
26	5.5		10.8
27	5.5		
28	5.5		10.3
29	5.5		
30	5.5		10.0
31	5.5		
32	5.5		9.3
33	5.5		
34	5.5		8.5
35	5.5		
36	5.5		8.3
37			
38	5.3		7.9
39			
40	5.0		7.5
41	5.0		7.5
42	5.0		7.5

TABLE 5. Water temperature in °C at various depths at Station 4 (Smith Mountain Dam), Smith Mountain Reservoir.

	1965	1966						
Depth m	Oct 22	Apr 8	May 7	Jun 7	Jun 17	Jul 2	Jul 23	Aug 30
0	17.2	8.0	17.0	24.0	25.0	29.5	26.1	26.0
1	17.1	8.0	16.0	24.5	25.0	28.0	25.7	26.0
2	17.1	8.0	16.0	23.0	24.5	28.0	24.6	26.0
3	17.1	8.0	15.0	18.0	24.5	27.0	22.8	24.2
4	17.1	8.0	15.0	18.0	24.0	21.0	20.0	23.0
5	17.1	8.0	14.5	18.0	22.0	19.0	17.9	20.2
6	17.1	8.0	14.0	17.0	15.5	17.5	16.7	18.0
7	17.1	8.0	13.0	14.0	14.0	15.5	16.3	17.2
8	17.0	8.0	13.0	13.0	14.0	14.0	16.0	17.0
9	17.0	8.0	11.5	12.0	13.0	14.0	15.8	17.0
10	17.0	8.0	10.0	11.0	12.5	13.5	15.8	16.5
11	16.1	8.0	9.5	11.0	12.0	13.0	15.6	16.3
12	16.0	8.0	9.0	11.0	12.0	13.0	15.5	16.1
13	15.2	8.0	9.0	11.0	12.0	13.0	15.2	16.0
14	14.5	8.0	8.5	10.5	12.0	12.0	15.1	16.0
15	14.2	8.0	8.0	10.5	11.5	12.0	15.0	15.8
16	14.1	8.0	8.0	10.0	11.5	12.0	14.8	15.5
17	13.5	8.0	8.0	10.0	11.0	12.0	14.7	15.5
18	13.5	8.0	8.0	10.0	11.0	12.0	14.4	15.5
19	13.5	8.0	8.0	10.0	10.5	11.5	14.4	15.2
20	13.0	8.0	8.0	9.5	10.0	11.5	14.3	15.0
21	13.0	8.0	8.0	9.0	10.0	11.0	14.2	15.0
22	13.0	8.0	8.0	9.0	10.0	11.0	14.1	15.0
23	13.0	8.0	7.5	9.0	9.5	11.0	14.1	15.0
24	12.2	8.0	7.5	9.0	9.0	11.0	14.0	14.8
25	12.0	8.0	7.5	8.5	9.0	11.0	13.8	14.5
26	12.0	8.0	7.5	8.0	9.0	11.0	13.6	14.5
27	11.9	8.0	7.0	8.0	9.0	11.0	13.3	14.5
28	11.5	8.0	7.0	8.0	9.0	10.5	12.9	14.5
29	11.2	8.0	7.0	8.0	8.5	10.0	12.7	14.1
30	11.0	8.0	7.0	8.0	8.5	10.0	12.6	14.1
31	11.0	8.0	7.0	N.B.	N.B.	N.B.	12.4	N.B.
32	N.B.	8.0	N.B.				12.3	
33		N.B.						
34								
35								
36								
37								
38								
39								
40								
41								
42								

N.B., "No Bottom," means that the temperature probe did not reach the lake bottom.

TABLE 5. Continued

	1966		1967				
Depth m	Nov 18	Dec 8	Jan 3	Feb 3	Mar 9	Apr 8	Aug 14
0	14.5	11.5	8.5	7.5	7.0	13.0	26.0
1	14.0	11.5	8.3	7.5			
2	14.0	11.5	8.2	7.5	6.5	12.7	25.5
3	14.0	11.3	8.1	7.5	6.5		
4	14.0	11.3	8.1	7.5	6.5	12.3	25.0
5	14.0	11.3	8.1	7.5			
6	14.0	11.3	8.1	7.5	6.0	11.5	21.5
7	14.0	11.3	8.1	7.5	6.0		
8	14.0	11.3	8.1	7.5	6.0	10.7	17.0
9	14.0	11.3	8.0	7.5	6.0		
10	14.0	11.2	8.0	7.5	6.0	10.0	15.0
11	14.0	11.2	8.0	7.5	6.0		
12	14.0	11.2	8.0	7.5	6.0	8.7	13.7
13	14.0	11.2	8.0	7.5	6.0		
14	14.0	11.2	8.0	7.5	6.0	8.5	13.3
15	14.0	11.2	8.0	7.5	6.0	8.5	
16	13.9	11.2	8.0	7.5	6.0	8.5	13.0
17	13.9	11.2	8.0		6.0		
18	13.9	11.2	8.0	7.3	6.0	8.3	12.7
19	13.9	11.2	8.0	7.3	6.0		
20	13.9	11.1	8.0	7.3	6.0	8.0	12.1
21	13.9	11.1	8.0	7.3	6.0	8.0	
22	13.9	11.1	8.0	7.3	6.0	8.0	11.5
23	13.9	11.1	8.0		6.0		
24	13.9	11.1	8.0	7.0	6.0	7.7	11.3
25	13.9	11.5	8.0	7.0	6.0		
26	13.9	11.5	8.0	7.0	6.0	7.3	10.9
27	13.9	11.5	8.0	7.0	6.0		
28	13.9	11.5	8.0	7.0	6.0	6.5	10.5
29	13.9	11.5	8.0	7.0	6.0	6.5	
30	13.8	11.5	8.0	7.0	6.0	6.5	10.3
31	13.8	11.5	8.0	7.0	6.0	6.5	
32	13.8	11.5	8.0	7.0	6.0	6.5	10.0
33	N.B.	11.5		7.0	6.0	6.5	
34		11.5		7.0	6.0	6.5	9.0
35		11.5		7.0	6.0	6.5	
36		11.5		7.0	6.0	6.5	8.7
37		11.5		7.0		6.5	
38		11.5		7.0	5.7	6.5	8.3
39		11.5		7.0			
40		11.5		7.0	5.5	6.3	8.0
41		11.5		7.0	5.5		
42		11.5		7.0	5.5	6.0	7.7

TABLE 6. Oxygen content in mg/l at various depths at Station 1 (Blackwater River arm), Smith Mountain Reservoir.

	1965		1966					
Depth m	Oct 22	Nov 20 YSI	May 7 YSI	Jun 17 YSI	Jul 2 YSI	Aug 30 YSI	Oct 17 YSI	Wink.
0	8.5	8.0	9.7	8.0	9.0	8.0	10.0	8.5
1	8.4	7.8	10.2	8.1	8.8	8.0	10.0	
2	8.4	7.8	12.5	8.4	9.8	8.0	10.4	
3	8.2	8.0	12.8	8.4	10.3	8.7	10.4	
4	8.2	8.0	12.5	8.7	10.5	8.4	10.4	
5	8.2	8.0	12.5	8.5	10.2	5.9	10.4	8.2
6	8.2	7.9	12.5	7.4	8.9	4.4		
7	8.2	7.6	12.8	7.0	7.6	3.7		
8	8.0	7.6	12.4	6.1	7.2	2.0*		
9	7.5	7.5	12.6	6.0	6.9	1.8*		
10	7.0	7.5	12.0	5.5	6.5	1.5*	10.5	
11	5.5	7.5	12.1	5.8	6.5	1.5*		
12	2.5	7.5	12.1	5.5	6.6	1.4*		
13	0.2	7.5	11.8	5.5	6.3	1.4*		
14	0.1	7.5	11.8	5.6	6.3	1.3*		
15	0.1	7.5	11.4	5.1	6.3	1.3*	4.8	0.2
16	0.1	7.5	11.8	5.3	6.3	1.1*		
17	0.1	7.5	11.4	5.4	6.4	1.1*		
18	0.1	7.5	11.6	5.4	5.9	1.1*		
19	0.1	7.5	N.B.	5.4	6.0	1.0*		
20	0.1	7.5		5.4	6.0	1.0*	3.5	
21	0.1	7.5		5.4	6.0	1.0*		
22	0.1	7.5		5.5	6.1	1.0*		
23	0.1	7.3		5.4	6.1	1.0*		
24	0.1	7.1		N.B.	6.2	1.0*		
25	0.1	6.5			6.2	1.0*	3.5	
26	0.1				6.2	1.0*		
27	0.1				6.3	1.0*	3.6	
28	0.1				6.0	0.9*		
29	0.1				6.0			
30	0.1				6.0			
31	0.1				N.B.			
32	N.B.							
33								
34								
35								
36								
37								
38								
39								
40								

*Estimated Values

N.B., "No Bottom," means that the temperature probe did not reach the lake bottom.

TABLE 6. Continued

Depth m	1966 Nov 18 Wink.	1966 Dec 8 YSI	1966 Dec 8 Wink.	1967 Feb 3 YSI	1967 Mar 9 YSI
0		8.8	8.8	11.1	11.9
1	6.3	8.8		11.1	11.9
2		8.8		11.1	11.9
3		9.5		11.1	11.9
4		9.5		11.1	11.9
5		9.5	8.8	11.1	11.9
6				11.1	11.9
7				11.1	11.9
8				11.1	11.9
9				11.1	11.9
10	6.8	12.5	8.8	11.1	11.9
11				11.1	11.9
12				11.1	11.9
13				11.1	11.9
14		12.0		11.1	11.9
15		12.5		11.1	11.9
16				11.1	11.8
17				11.1	11.8
18		11.6	8.5	11.1	11.8
19				11.0	11.8
20	6.3			10.9	11.8
21				10.9	11.8
22				10.9	11.8
23				10.9	11.8
24				10.9	11.8
25				10.9	11.8
26				10.9	11.9
27				10.9	
28	6.0			10.9	
29				10.9	
30				10.9	
31				10.9	
32				10.9	
33				10.9	
34				10.9	
35				10.9	
36				10.9	
37				10.9	
38				10.9	
39					
40				9.9	

TABLE 7. Oxygen content in mg/l at various depths at Station 2 (Roanoke River arm), Smith Mountain Reservoir.

1966

Depth m	Apr 8 Wink.	May 7 YSI	Jun 17 YSI	Jul 2 YSI	Jul 30 YSI	Aug 17 YSI	Aug 17 Wink.	Oct 18 Wink.	Nov 26 Wink.
0	12.2	10.5	8.0	7.0	8.0	9.5	8.5		6.7
1		10.0	8.6	6.8	8.4	9.7		5.9	
2		12.5	9.3	8.6	8.3	9.3			
3		12.9	9.3	8.9	8.4	9.3			
4		12.7	9.0	7.2	7.6	9.3			
5	12.6	12.7	8.2	8.0	5.5	9.8	8.4		
6		12.4	8.1	7.9	4.4				
7		12.8	7.6	7.0	2.0*				
8		12.0	6.7	5.5	1.5*				
9		12.8	6.5	5.6	1.3*				
10	12.4	12.4	6.2	5.8	1.3*	8.5		6.4	
11		12.4	6.3	5.5	1.3*	6.2			
12		12.0	5.8	5.6	1.2*	4.8			
13		12.4	5.8	5.0	1.0*	4.4			
14		12.2	5.5	5.3	1.0*	4.2			
15		12.2	5.5	5.3	1.0*	3.8			5.5
16		11.7	5.5	5.4	1.0*	3.5			
17		11.7	5.5	5.4	1.0*	3.4			
18		11.7	5.5	5.5	1.0*	3.4			
19		11.7	5.5	5.5	1.0*	3.4			
20		11.7	5.8	5.5	1.0*	3.4	0.3	5.7	
21		12.0	5.9	5.3	0.9*				
22		11.7	5.9	5.4	0.8*				
23	9.1	11.8	5.9	5.4					
24		11.4	5.9						
25		11.4	5.5			2.8*			
26		11.4	5.5						
27		11.4	5.5						
28		11.4	5.5						5.2
29		11.0	5.5						
30		10.9	5.5			2.8*			
31		11.1	N.B.			N.B.			
32		N.B.						0.2	
33								N.B.	
34									
35									
36									
37									
38									
39									
40									

*Estimated Values

N.B., "No Bottom," means that the temperature probe did not reach the lake bottom.

TABLE 7. Continued

Depth m	1966 Dec 8 YSI	1966 Dec 8 Wink.	1967 Jan 3 Wink.	1967 Feb 3	1967 Mar 9
0	7.2	8.4	8.9	11.1	12.1
1	7.0			11.1	12.1
2	7.1			11.1	12.1
3	7.1			11.1	12.1
4				11.1	12.1
5	7.4	8.1	8.7	11.1	12.0
6				11.1	11.8
7				11.1	11.8
8				11.1	11.8
9				11.1	11.8
10	7.6			11.1	11.8
11				11.1	11.8
12				11.1	11.8
13				11.1	11.8
14				11.1	11.8
15	10.5	7.9	8.7	11.1	11.8
16				11.1	11.4
17				11.1	11.4
18				11.1	11.4
19				10.8	11.4
20	10.7			9.6	11.4
21				9.6	11.4
22				9.6	11.4
23				9.6	11.4
24				9.6	11.4
25	10.8			9.6	11.4
26			8.6	9.6	11.8
27				9.6	11.8
28				9.6	11.8
29				9.6	11.8
30	12.8	8.1		9.6	11.8
31				9.6	11.8
32				9.6	11.8
33				9.6	11.8
34				9.6	11.8
35	12.8	8.3		9.6	11.8
36	13.0			9.6	11.3
37				9.6	
38				9.6	
39				9.6	
40				9.7	

TABLE 8. Oxygen content in mg/l at various depths at Station 3 (confluence of Blackwater and Roanoke Rivers), Smith Mountain Reservoir.

	1966								1967
Depth m	May 7 Wink.	Jul 2 YSI	Aug 30 YSI	Aug 30 Wink.	Nov 26 YSI	Nov 26 Wink.	Dec 8 YSI	Dec 8 Wink.	Apr 8
0	11.1	7.8	7.5	8.8	6.5	6.9	10.0	8.5	12.9
1		7.9	7.6		6.7		10.4		12.9
2		7.9	8.0		6.7		10.0		12.9
3		8.4	7.8		6.3		10.0		12.9
4		8.4	8.3		6.5		10.0		12.9
5	11.4	8.3	5.3	5.3	6.5	6.2	10.8	8.4	12.9
6		7.5	3.8		6.3				12.9
7		7.1	2.5*		6.4				12.9
8		6.2	1.8*		6.5				12.9
9		6.0	1.8*		6.3				12.8
10	11.0	5.3	1.8*	1.9	6.3	6.3	10.0		12.7
11		5.3	1.5*						12.7
12		5.3	1.5*						12.7
13		5.4	1.5*						12.7
14		5.5	1.5*						12.7
15	12.1	5.5	1.5*	1.6	6.3		10.2	8.1	12.7
16		5.5	1.3*						12.7
17		5.5	1.3*						12.7
18		5.5	1.3*						12.7
19		5.6	1.2*						12.7
20	11.8	5.6	1.2*		6.2	6.2	11.0		12.7
21		5.6	1.2*						12.7
22		5.6	1.0*						12.7
23		5.5	1.0*						12.5
24		5.5	1.0*						12.0
25		5.5	1.0*	0.9	6.1		11.8		
26		5.3	1.0*						
27		5.3	1.0*						
28		5.3	1.0*						
29		5.3	1.0*						
30		5.3	1.0*		4.7	3.6	11.8	8.0	
		N.B.	N.B.		N.B.				
35							11.3		
40							11.4	8.0	
45							11.4		
50							11.0		

*Estimated Values

N.B., "No Bottom," means that the temperature probe did not reach the lake bottom.

TABLE 9. Oxygen content in mg/l at various depths at Station 4 (Smith Mountain Dam), Smith Mountain Reservoir.

	1965	1966						
Depth m	Oct 22 YSI	May 7 Wink.	Jun 7 Wink	Jun 17 YSI	Jul 2 YSI	Aug 30 YSI	Aug 30 Wink.	Nov 18 Wink.
0	8.5	12.2	8.7	9.5	9.5	7.5	8.9	
1	8.4			8.8	9.5	7.5		6.8
2	8.4			9.0	9.3	7.5		
3	8.2			9.2	9.6	6.9		
4	8.2			9.2	9.1	6.5		
5	8.2	11.9	8.8	8.4	8.0	4.3	5.1	5.9
6	8.2			6.7	7.6	2.5*		
7	8.2			6.6	7.0	2.3*		
8	8.0			6.3	6.9	2.0*		
9	7.5			6.1	6.5	2.0*		
10	7.0	9.8	6.8	5.8	6.5	2.0*	2.3	
11	5.7			6.0	6.3	2.0*		
12	2.5*			5.6	6.2	1.9*		
13	0.2*			5.6	6.2	1.8*		
14	0.1*			5.6	6.3	1.8*		
15	0.0*	9.4	6.9	5.6	6.5	1.5*	2.0	5.7
16	0.0*			5.6	6.5	1.5*		
17	0.0*			5.7	6.5	1.5*		
18	0.0*			5.7	6.5	1.5*		
19	0.0*			5.5	6.2	1.5*		
20	0.0*	8.8	7.2	5.6	6.2	1.4*		
21	0.0*			5.6	5.8	1.4*		
22	0.0*			5.6	5.8	1.4*		
23	0.0*			5.3	5.8	1.3*		
24	0.0*			5.3	5.8	1.2*		
25	0.0*			5.3	5.8	1.2*	1.1	5.6
26	0.0*			5.3	5.8	1.2*		
27	0.0*			5.3	5.8	1.1*		4.6
28	0.0*			5.3	5.9	1.1*		
29	0.0*			5.4	6.0	1.1*		4.6
30	0.0*			5.4	6.0	1.1*		
31	0.0*			N.B.	N.B.	N.B.		
	N.B.							

*Estimated Values

N.B., "No Bottom," means that the temperature probe did not reach the lake bottom.

TABLE 9. Continued

Depth m	1966 Dec 8 YSI	1966 Dec 8 Wink.	1967 Jan 3 Wink.	1967 Feb 3	1967 Mar 9	1967 Apr 8
0	9.0	7.7	8.9	10.7	11.7	
1	9.2					
2	8.8					
3	9.0					
4	9.2					
5	9.3	7.5	8.8			
6	9.4				11.8	
10	10.2		9.0			12.0
15	10.4	7.5				
16	10.4				11.7	
20	10.5		8.8	10.4		
25	11.0					
30	10.5	7.1	8.7			
35	10.5					
36					11.5	
40				10.0		11.7
45	11.0					
46					11.3	
50	11.1					
52	10.6					

TABLE 10. Alkalinity in mg $CaCo_3$/l at various depths at Station 1 (Blackwater River arm) as determined during primary productivity estimates in the Smith Mountain Reservoir.

	1965	1966					
Depth m	Oct 22	Jan 8	Apr 8	Jun 17	Jul 26	Oct 17	Dec 15
0	70	85	68	71	73	73	76
1	71	85	69	69	72	75	77
2	64	81	70	69	71	75	78
3	70	80	69	72	72	78	78
4	64	83	69	74	76	76	78
5	70	82	69	77	76	81	78
6	64	81		76	77		78
7	64	81			77	81	
8	70	78	69	76			78
9	64	80			79	79	
10	72	83		77			78
11	71	83			78		
12	73	80	69				
13	75	81			79		
14	76	77					

TABLE 11. Alkalinity in mg $CaCO_3$/l at various depths at Station 2 (Roanoke River arm) as determined during primary productivity estimates in the Smith Mountain Reservoir.

	1966				
Depth m	Apr 8	Jun 17	Jul 26	Oct 17	Dec 15
0	87	84	84	82	83
1	85	83	84	83	87
2	84	84	82	84	86
3	87	85	81	82	86
4	86	83	81	82	85
5		83	79	84	85
6	87	80	79		85
7			79	84	
8	88	77			86
9			79	84	
10	88	78			88
11			78		
12					
13			78		

TABLE 12. Alkalinity in mg $CaCO_3$/l at various depths at Station 3 (Confluence of Blackwater and Roanoke Rivers) as determined during primary productivity estimates in the Smith Mountain Reservoir.

	1966				1967
Depth m	May 7	Jul 2	Aug 29	Nov 26	Aug 14
0	70	79	76	79	88
1	74	79	78	79	86
2	73	79	80	79	87
3	72		76	79	87
4	77	73	79	79	
5	73	75	80	79	86
6		73		78	85
7	74	76	78	78	83
8					79
9	78	76	80	78	
10					75
11	78	76	80	78	
12					75
13		76			
14					
15		78			
20		77			

TABLE 13. Alkalinity in mg $CaCO_3$/l at various depths at Station 4 (Smith Mountain Dam) as determined during primary productivity estimates in the Smith Mountain Reservoir.

	1966				1967
Depth m	May 7	Jul 2	Aug 29	Nov 26	Aug 14
0	71	75	80	74	87
1	72	76	80	74	87
2	70	75	81	74	88
3	73	75	82	76	87
4	74	74	82	75	88
5	76	75	82	76	87
6	72	76		76	86
7	74	76	81	76	78
8	73			76	77
9	72	79	77		
10	75			76	76
11	75	76	80		
12				76	75
13		73			

TABLE 14. pH at various depths at Station 1 (Blackwater River arm), Smith Mountain Reservoir.

Depth m	1965 Oct 22	1966 Jan 8	Apr 8	Jun 17	Jul 26	Oct 17	Dec 16
0	7.6	7.4	7.7	8.3	8.1	7.5	7.5
1	7.6	7.6	7.8	8.0	8.1	7.5	7.5
2	7.6	7.4	7.8	8.2	8.1	7.5	7.5
3	7.5	7.3	7.7	8.2	8.1	7.5	7.4
4	7.5	7.3	7.6	8.1	7.5	7.5	7.4
5	7.5	7.4	7.8	7.9	7.2	7.5	7.4
6	7.5	7.1		7.6	7.0		7.5
7	7.4	7.3			7.1	7.5	
8	7.5	7.3	7.7	7.2			7.5
9	7.2	7.1			7.0	7.3	
10	6.9	7.3		7.3			7.5
11	6.9	7.4			7.1		
12	6.8	7.3	7.8				
13	6.8	7.7			7.0		
14	6.8	7.3					

TABLE 15. pH at various depths at Station 2 (Roanoke River arm), Smith Mountain Reservoir.

Depth m	1966 Apr 8	Jun 17	Jul 26	Oct 17	Dec 16
0	7.9	8.3	8.2	7.5	7.4
1	7.9	8.3	8.2	7.5	7.5
2	8.0	8.5	8.1	7.6	7.4
3	7.9	8.4	8.1	7.6	7.4
4	8.0	8.4	7.8	7.6	7.4
5		7.9	7.2	7.6	7.4
6	8.0	7.7	7.1		7.4
7			7.1	7.5	
8	8.0	7.3			7.4
9			7.1	7.4	
10	8.0	7.2			7.4
11			7.1		
12	8.0				
13			7.0		
20		7.3			

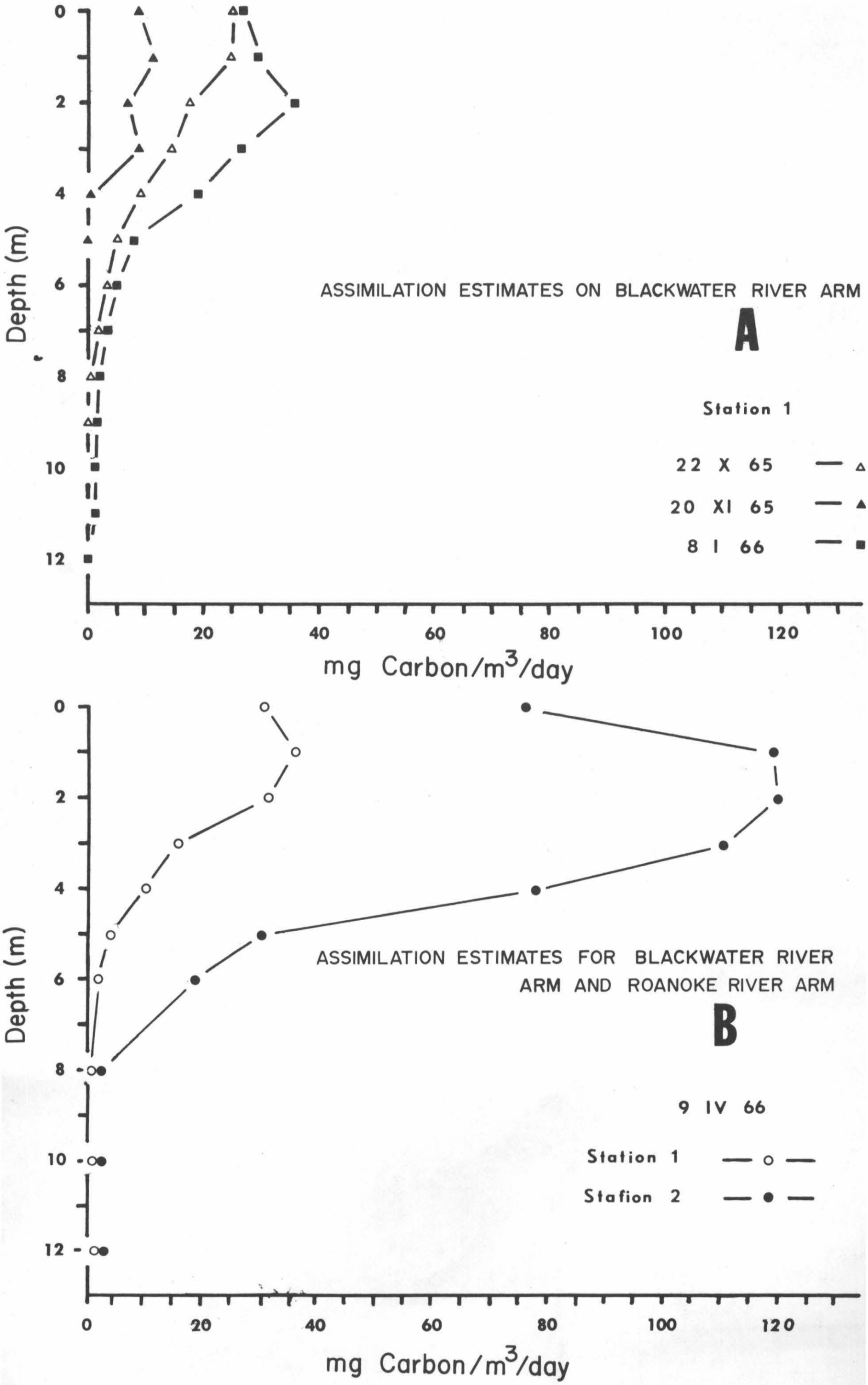
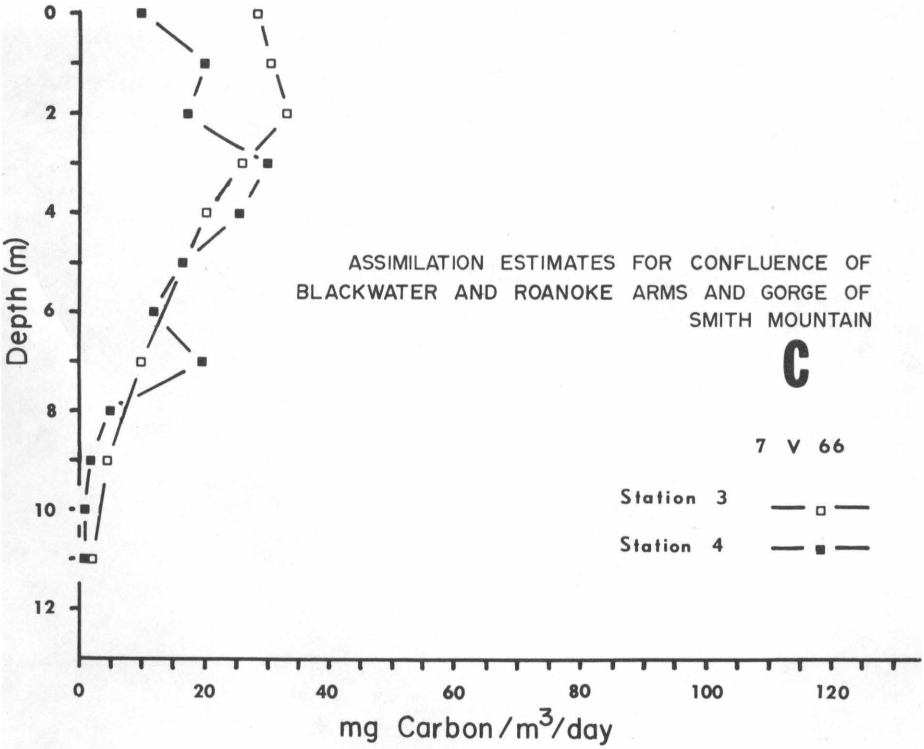
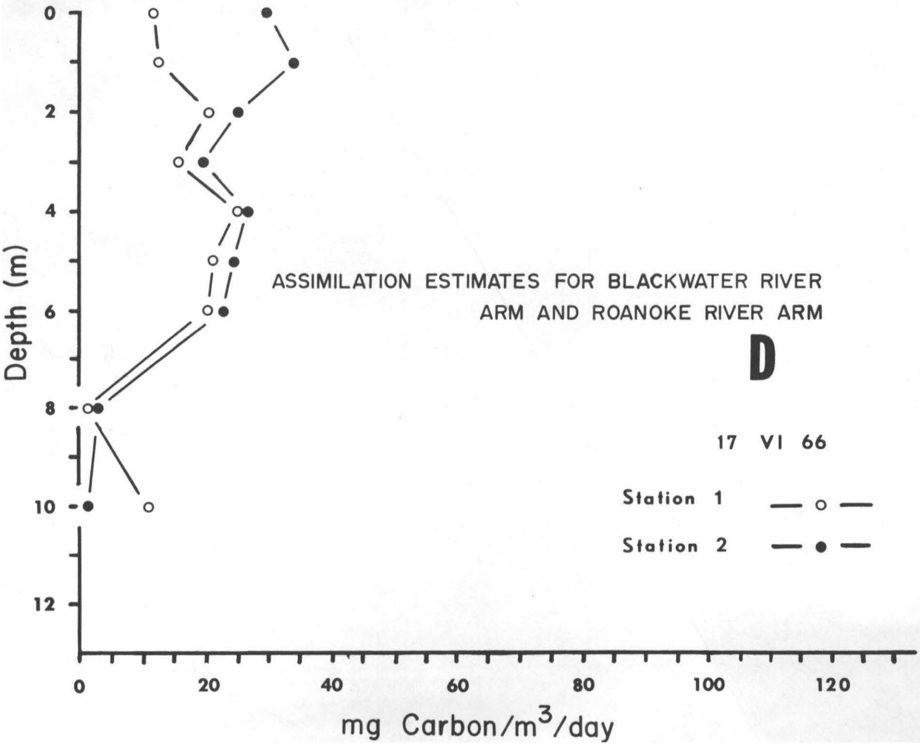


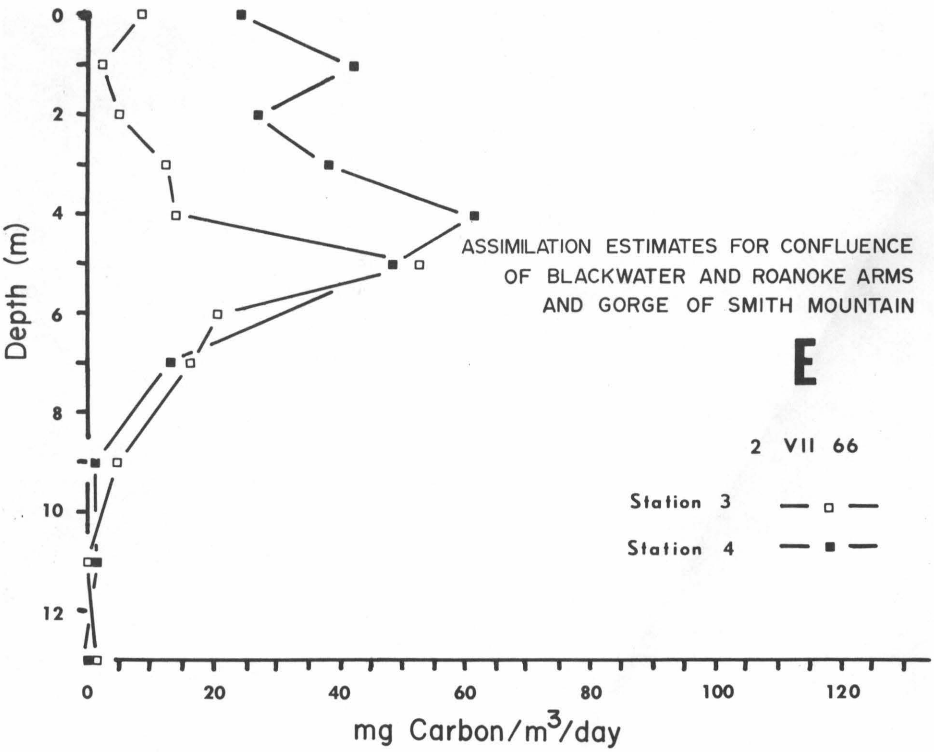
Figure 4. Primary productivity curves in Smith Mountain Reservoir.

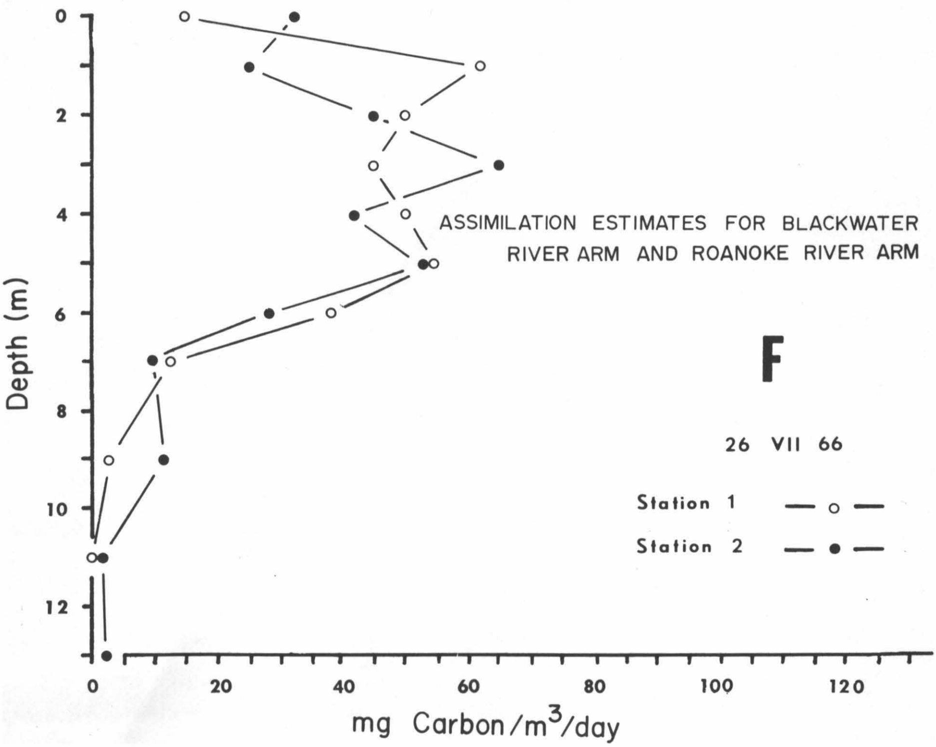


ASSIMILATION ESTIMATES FOR CONFLUENCE OF BLACKWATER AND ROANOKE ARMS AND GORGE OF SMITH MOUNTAIN
C
7 V 66
Station 3
Station 4
Depth (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
mg Carbon/m3/day



ASSIMILATION ESTIMATES FOR BLACKWATER RIVER ARM AND ROANOKE RIVER ARM
D
17 VI 66
Station 1
Station 2
Depth (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
mg Carbon/m3/day


ASSIMILATION ESTIMATES FOR CONFLUENCE OF BLACKWATER AND ROANOKE ARMS AND GORGE OF SMITH MOUNTAIN
E
2 VII 66
Station 3
Station 4
Depth (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
mg Carbon/m3/day


ASSIMILATION ESTIMATES FOR BLACKWATER RIVER ARM AND ROANOKE RIVER ARM
F
26 VII 66
Station 1
Station 2
Depth (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
mg Carbon/m3/day

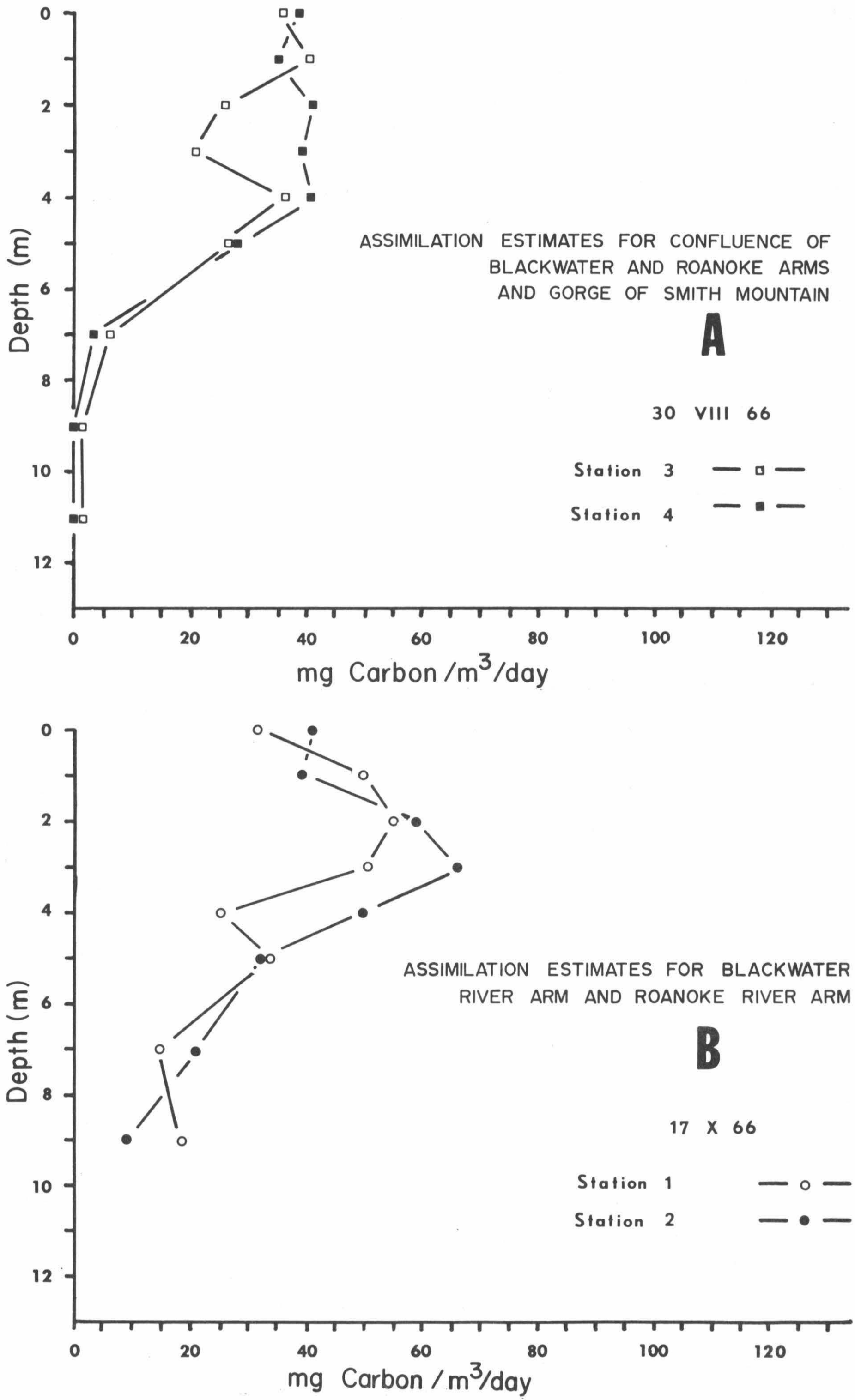
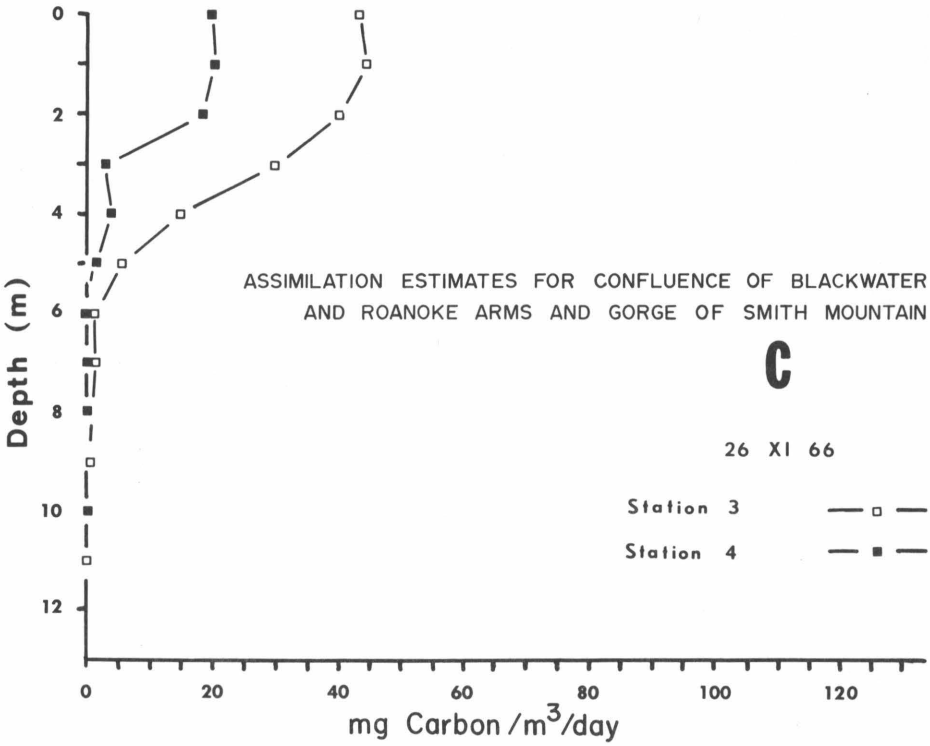
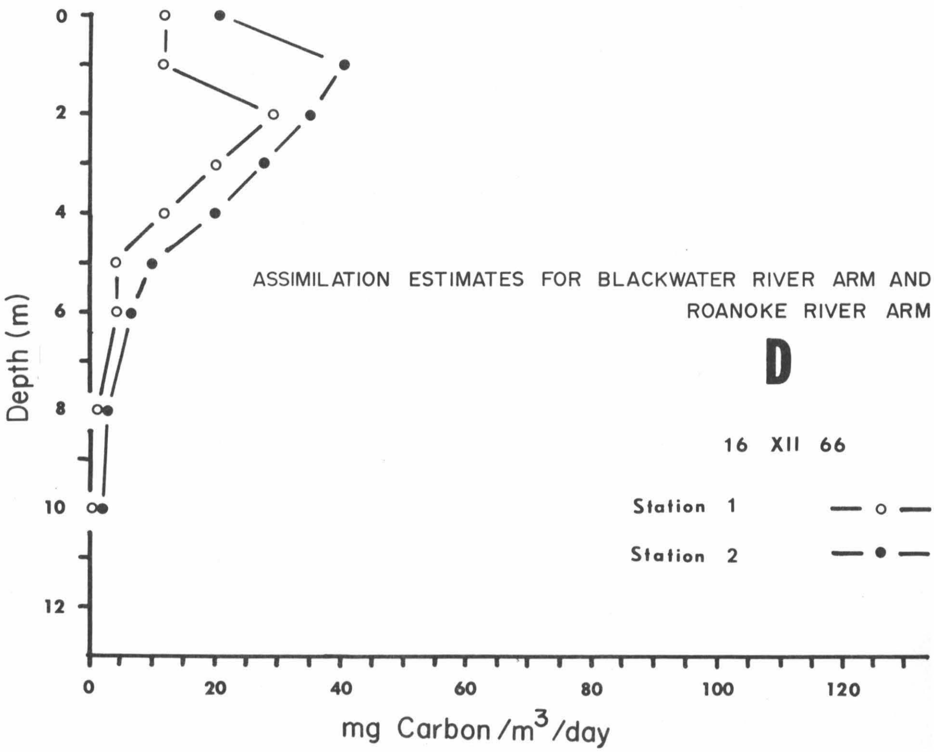


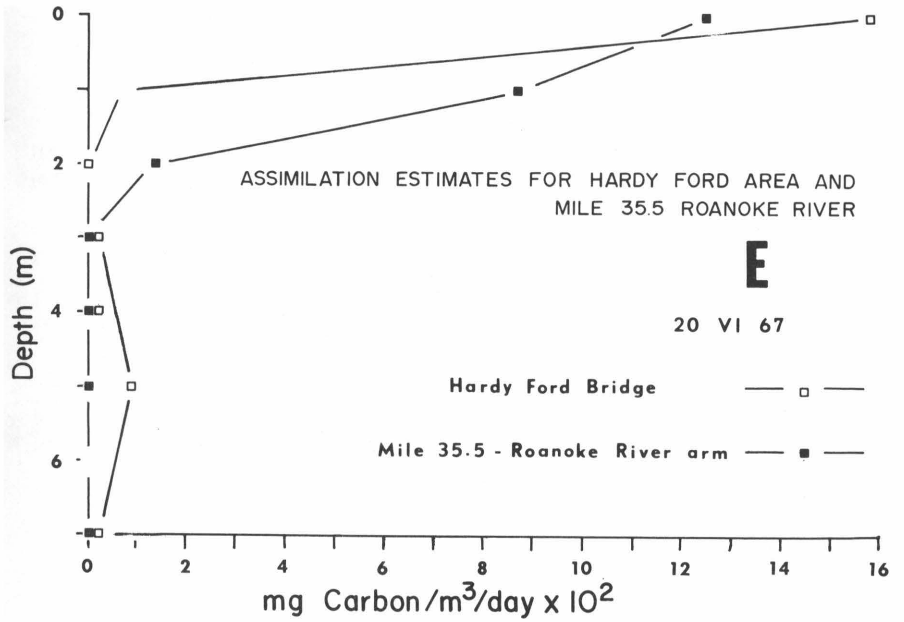
Figure 5. Primary productivity curves in Smith Mountain Reservoir.



ASSIMILATION ESTIMATES FOR CONFLUENCE OF BLACKWATER AND ROANOKE ARMS AND GORGE OF SMITH MOUNTAIN
C
26 XI 66
Station 3
Station 4
Depth (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
mg Carbon / m3/day



ASSIMILATION ESTIMATES FOR BLACKWATER RIVER ARM AND ROANOKE RIVER ARM
D
16 XII 66
Station 1
Station 2
Depth (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
mg Carbon / m3/day


ASSIMILATION ESTIMATES FOR HARDY FORD AREA AND
MILE 35.5 ROANOKE RIVER
E
20 VI 67
Hardy Ford Bridge
Mile 35.5 - Roanoke River arm
Depth (m)
0
2
4
6
0
2
4
6
8
10
12
14
16
mg Carbon/m3/day x 10^2

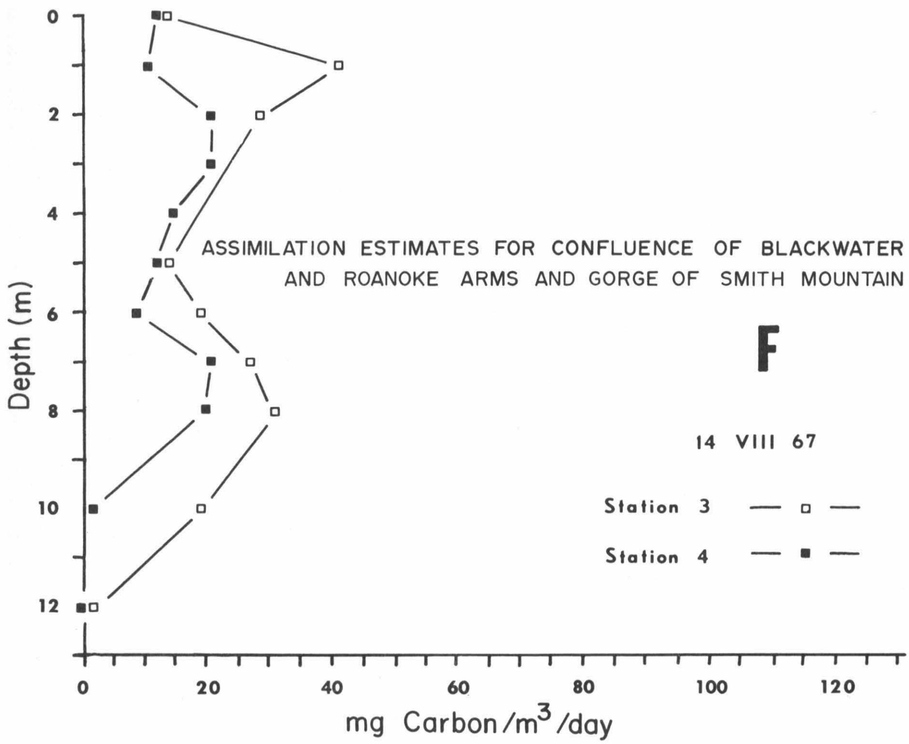

ASSIMILATION ESTIMATES FOR CONFLUENCE OF BLACKWATER
AND ROANOKE ARMS AND GORGE OF SMITH MOUNTAIN
F
14 VIII 67
Station 3
Station 4
Depth (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
mg Carbon/m3/day

TABLE 16. pH at various depths at Station 3 (confluence of Blackwater and Roanoke Rivers), Smith Mountain Reservoir.

	1966				1967
Depth m	May 7	Jul 2	Aug 29	Nov 25	Aug 14
0	7.7	8.2	8.4	7.2	8.8
1	7.8	8.3	8.4	7.2	8.6
2	7.7	8.3	8.4	7.3	8.7
3	7.7		8.5	7.3	8.7
4	7.8	8.0	8.5	7.3	
5	7.7	7.5	7.9	7.3	8.6
6		7.2		7.3	8.5
7	7.6	7.1	7.1	7.3	8.3
8					7.9
9	7.6	7.2	7.1	7.3	
10					7.5
11	7.4	7.2	7.1	7.3	
12					7.5
13		7.1			
14					
15	7.1				
20		7.1			
40			6.8		

TABLE 17. pH at various depths at Station 4 (Smith Mountain Dam), Smith Mountain Reservoir.

	1966				1967
Depth m	May 7	Jul 2	Aug 29	Nov 25	Aug 14
0	7.7	8.3	8.4	7.2	8.7
1	7.7	8.3	8.4	7.1	8.7
2	7.6	8.3	8.5	7.1	8.8
3	7.6	8.3	8.4	7.1	8.7
4	7.7	7.9	8.0	7.1	8.8
5	7.8	7.4	7.2	7.1	8.7
6	7.6	7.1		7.1	8.6
7	7.7	7.1	7.2	7.1	7.8
8	7.5			7.1	7.7
9	7.3	7.1	7.1		
10	7.3			7.1	7.6
11	7.2	7.1	7.0		
12				7.1	7.5
13		6.6			
20		7.0			
40			6.7		

stratification, there is a large hypolimnetic volume compared to the volume of the epilimnion. This is a condition that accounts for the summer oxygen distribution and has permitted the reservoir to accommodate the inflow of oxidizable materials from the upper reaches.

In terms of inorganic carbon assimilation, the Roanoke River sampling station usually yielded higher estimates than the Blackwater River station (Fig. 4, 5). In December 1966, the Blackwater arm yielded 98.7 mg $C/m^2/day$, while the Roanoke arm yielded an estimate of 171.1 mg $C/m^2/day$ (Fig. 5D, Tables 18, 19). Early spring experiments (April 1966) emphasize the difference between the two arms of the impoundment. On the Blackwater arm, 140.2 mg $C/m^2/day$ were assimilated, while 575.2 mg $C/m^2/day$ were assimilated on the Roanoke arm - a four-fold increase. Summer estimates confirmed the increased production on the Roanoke arm, but not with the great differences observed in April. The June experiment showed 176.4 mg $C/m^2/day$ on the Blackwater arm and 198.9 mg $C/m^2/day$ on the Roanoke arm.

The differences between the two parts of the impoundment prompted further investigation of the upper reaches of the Roanoke River arm. Experiments carried out in June, 1967, showed a ten-fold increase in carbon assimilation over the other sampling stations. The estimates were 1804.0 mg $C/m^2/day$ at Hardy Ford and 2286.0 mg $C/m^2/day$ at Mile 35.5, about midway between Hardy and Hale Ford. Although these results are not as great as estimates obtained from highly eutrophic lakes (Wetzel, 1966), the yields do compare rather closely with estimates that have been obtained from lakes which are receiving enrichment from various influents (Rodhe, 1967). These yields illustrate dramatically the effects of enrichment by municipal effluents.

Even after the initiation of chlorination procedures by the Roanoke sewage treatment plant in February, 1968, the effluent still contained sufficient nutrients to maintain the high levels of carbon assimilation. Estimates of productivity made in June, 1968 were almost identical as those of the previous year. At Hardy Ford Bridge, the estimate was 1808.2 mg $C/m^2/day$, while the estimate rate at Mile 35.5 was 2034.9 mg $C/m^2/day$. Nutrient levels (nitrate and phosphorus) were at the same levels as they had been in 1967, and, from total coliform MPN estimates made during 1967 and during the 1968 season, chlorination was not very effective in reducing total coliform counts at the Hardy Ford Bridge area (see below).

TABLE 18. mg Carbon assimilated per m^3 per day at various depths at Station 1 (Blackwater River arm), Smith Mountain Reservoir.

	1965		1966					
Depth m	Oct 22	Nov 20	Jan 8	Apr 9	Jun 17	Jul 26	Oct 17	Dec 16
0	24.8	8.1	26.3	31.2	12.3	14.5	33.4	12.8
1	24.6	11.2	29.3	36.4	12.7	62.8	49.6	12.1
2	18.1	7.6	36.1	32.8	20.2	50.3	55.6	28.0
3	13.9	9.4	27.0	19.7	15.6	44.8	50.9	19.4
4	9.3	0.2	19.2	10.4	24.1	50.0	26.6	12.2
5	5.2	0.0	8.8	4.6	21.0	55.3	33.9	4.0
6	3.7	0.0	4.4	1.7	20.5	38.0	26.0	4.2
7	2.6	0.0	2.1	0.8	17.2	12.7	15.9	3.3
8	0.8	0.0	0.4	0.4	2.4	7.2	17.5	1.5
9	0.0	0.0	0.2	0.1	6.0	3.5	18.8	1.2
10	0.0	0.0	0.2	0.1	10.2	1.2	15.5	0.0
11	0.0	0.0	0.2	0.4	8.4	0.0	8.0	0.0
12	0.0	---	0.0	0.7	4.6			
13	0.0	0.0	0.0	0.5	1.2			
14	0.0	---	0.0	0.4	0.0			
15	0.0	---	0.0	0.0	0.0			
TOTAL	103.0	36.5	154.2	104.2	176.4	340.3	351.7	98.7

(mg C/m^2/day)

TABLE 19. mg Carbon assimilated per m^3 per day at various depths at Station 2 (Roanoke River arm), Smith Mountain Reservoir.

	1966				
Depth m	Apr 9	Jun 17	Jul 26	Oct 17	Dec 16
0	77.0	31.0	32.7	42.3	21.6
1	119.8	34.0	25.1	38.5	40.3
2	120.0	25.4	44.9	59.0	34.7
3	112.4	19.7	64.9	66.1	27.6
4	78.9	24.5	42.1	48.9	19.5
5	30.9	23.5	54.9	33.8	9.2
6	18.9	22.1	23.1	27.3	7.5
7	12.0	12.5	9.7	21.5	5.1
8	4.7	3.5	10.6	15.0	2.7
9	2.0	2.0	11.6	9.0	1.9
10	0.2	0.7	7.3	4.5	1.0
11	0.2	0.0	2.9	0.0	0.0
12	0.2	0.0	3.0	0.0	0.0
13	0.0	0.0	3.4	0.0	0.0
TOTAL (mg C/m^2/day)	575.2	198.9	336.2	365.9	171.1

TABLE 20. mg Carbon assimilated per m^3 per day at various depths at Station 3 (confluence of Blackwater and Roanoke Rivers), Smith Mountain Reservoir.

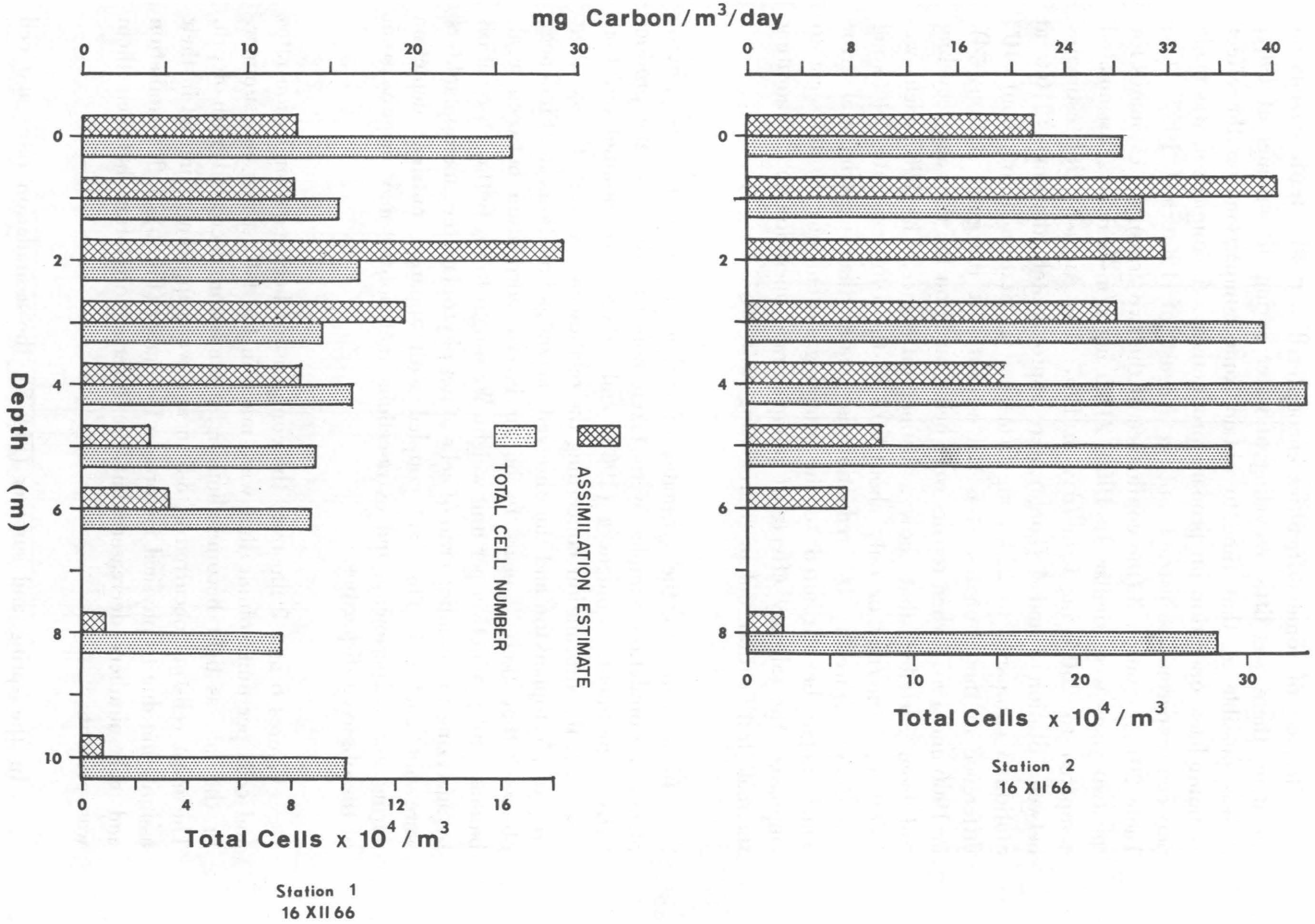
	1966				1967
Depth m	May 7	Jul 2	Aug 30	Nov 26	Aug 14
0	28.6	8.4	36.2	42.9	22.9
1	30.3	2.4	40.7	44.3	41.4
2	32.9	4.8	26.3	39.3	28.0
3	25.8	13.3	22.6	29.9	24.0
4	20.0	13.9	36.4	14.9	19.0
5	9.8	52.9	26.9	5.5	14.8
6	9.9	19.3	14.5	1.4	19.6
7	10.0	16.6	7.0	1.6	26.4
8	7.0	11.0	6.0	1.0	32.3
9	4.3	4.7	0.0	0.4	----
10	3.0	2.0	0.0	0.1	20.0
11	1.8	2.0	0.0	0.0	----
12	1.0	----	0.0	----	2.3
13	0.0	1.6	0.0	----	0.0
TOTAL (mg C/m^2/day)	184.4	150.3	216.6	181.3	250.7

Because of some difficulties encountered with the trash screens on the dam, there was little recycling of water during the summer of 1967. It was possible at that time to obtain some comparisons on the effect of pump-back operation on primary productivity. A comparison was made between experiments carried out in August of 1966 and 1967. (see Table 20) At Station 3 (the confluence of the two arms), the estimates for the two years were similar. In 1966, 216.6 mg C/m^2/day was assimilated compared to 250.7 mg C/m^2/day in 1967. The August, 1966 estimates between Station 3 and 4 (gorge) were approximately the same (216.6 at Station 3 compared to 244.4 mg C/m^2/day at Station 4) or about a 10% difference in the estimates. It is the estimates at the gorge station (#4) in 1966 and 1967, when repairs were being made on the dam and recycling had been curtailed, that show a distinct difference. The 1967 yield was 149.9 mg C/m^2/day or only about 60% of the 1966 estimate (244.4 mg C/m^2/day). Since a 40% reduction is greater than experimental error which might be attributed to the sampling system, the results seem to emphasize the salutary effects of pump-storage operation in ameliorating thermal stratification and in recirculating nutrients.

In addition to the estimates of carbon assimilation rates, phytoplankton population samples were taken concurrently with the productivity experiments. Findenegg (1965) and others have pointed out that there is little information concerning the relationship between the standing crop of phytoplankton and the observed carbon assimilation rate. Findenegg observed that there appears to be an inverse correlation between algal biomass and production per unit weight. We sought to verify this observation by analyzing the standing crop of cells of net phytoplankters; nannoplankters were not analyzed. This fact coupled with apparent nutrient depletion during some experiments and extra-cellular metabolities may magnify some of the observed disparities.

Figures 6 and 7 illustrate the comparisons between assimilation rates and cells per unit volume that were made in the fall, spring and summer. In the fall, as light becomes limiting, assimilation decreased with depth. The most cells/m^3 occurred at 3-5 m and were apparently limited in their assimilation due to physical factors. In December (Fig. 6), both assimilation and cell numbers decreased, but the inverse correlation between them was evident.

In the spring and summer (Fig. 7), the assimilation rates and cell numbers accentuate the inverse correlation that Findenegg proposed. There


mg Carbon / m^3/ day
0
10
20
30
0
8
16
24
32
40
Depth (m)
0
2
4
6
8
10
ASSIMILATION ESTIMATE
TOTAL CELL NUMBER
0
4
8
12
16
Total Cells x 10^4 / m^3
0
10
20
30
Total Cells x 10^4 / m^3
Station 1
16 XII 66
Station 2
16 XII 66

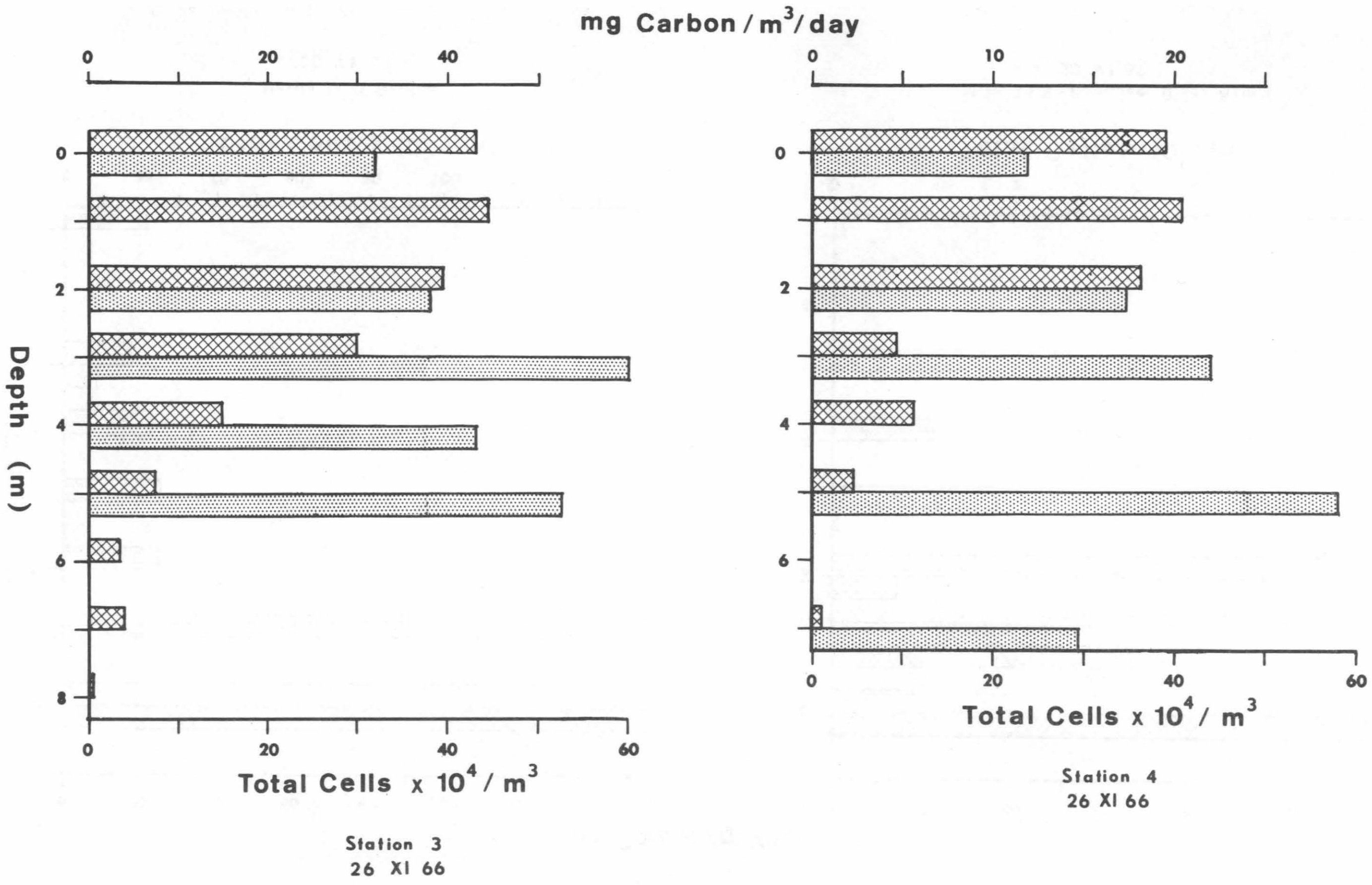
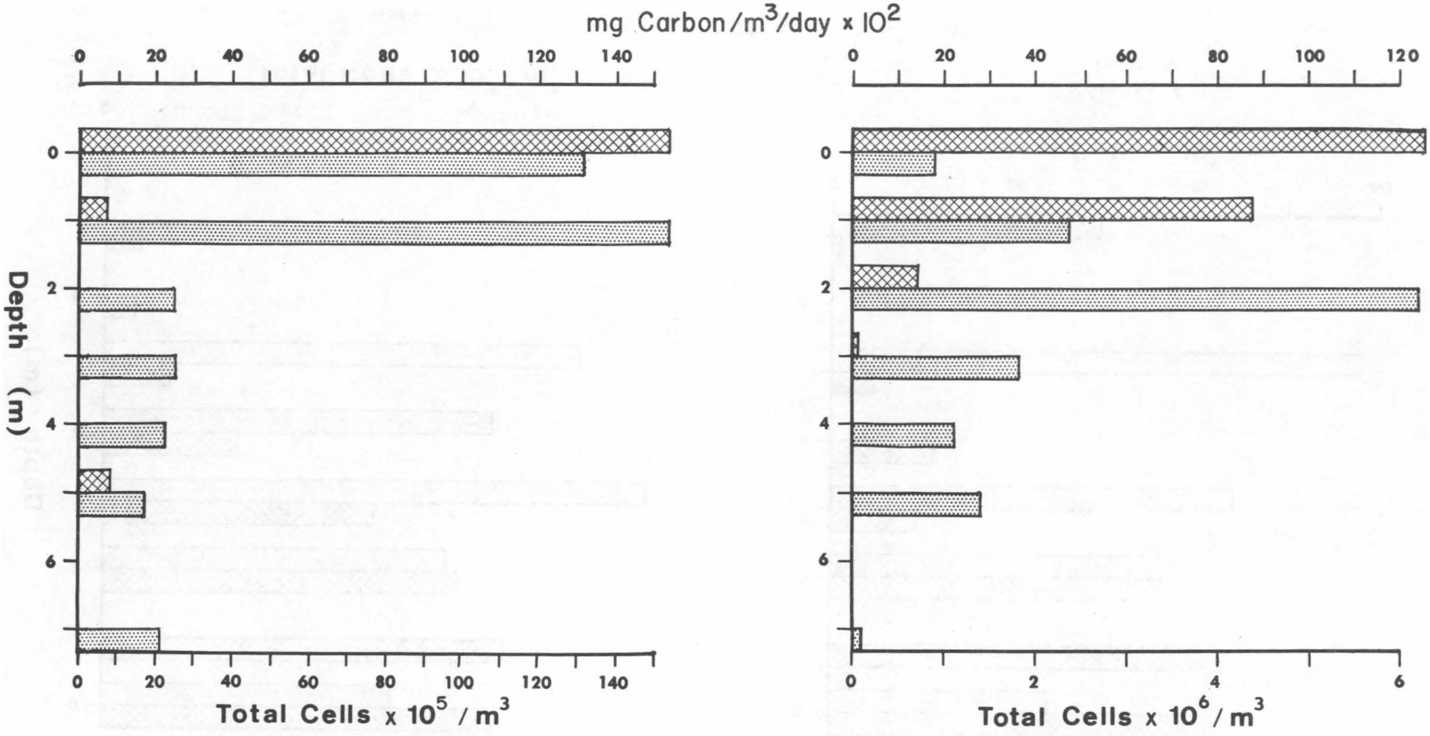


Figure 6. Histograms of the relationship between primary productivity estimates and total net phytoplankton cell numbers, 26 November and 16 December 1966.



Hardy Ford Bridge
20 VI 67

Mile 35.5 - Roanoke River Arm
20 VI 67

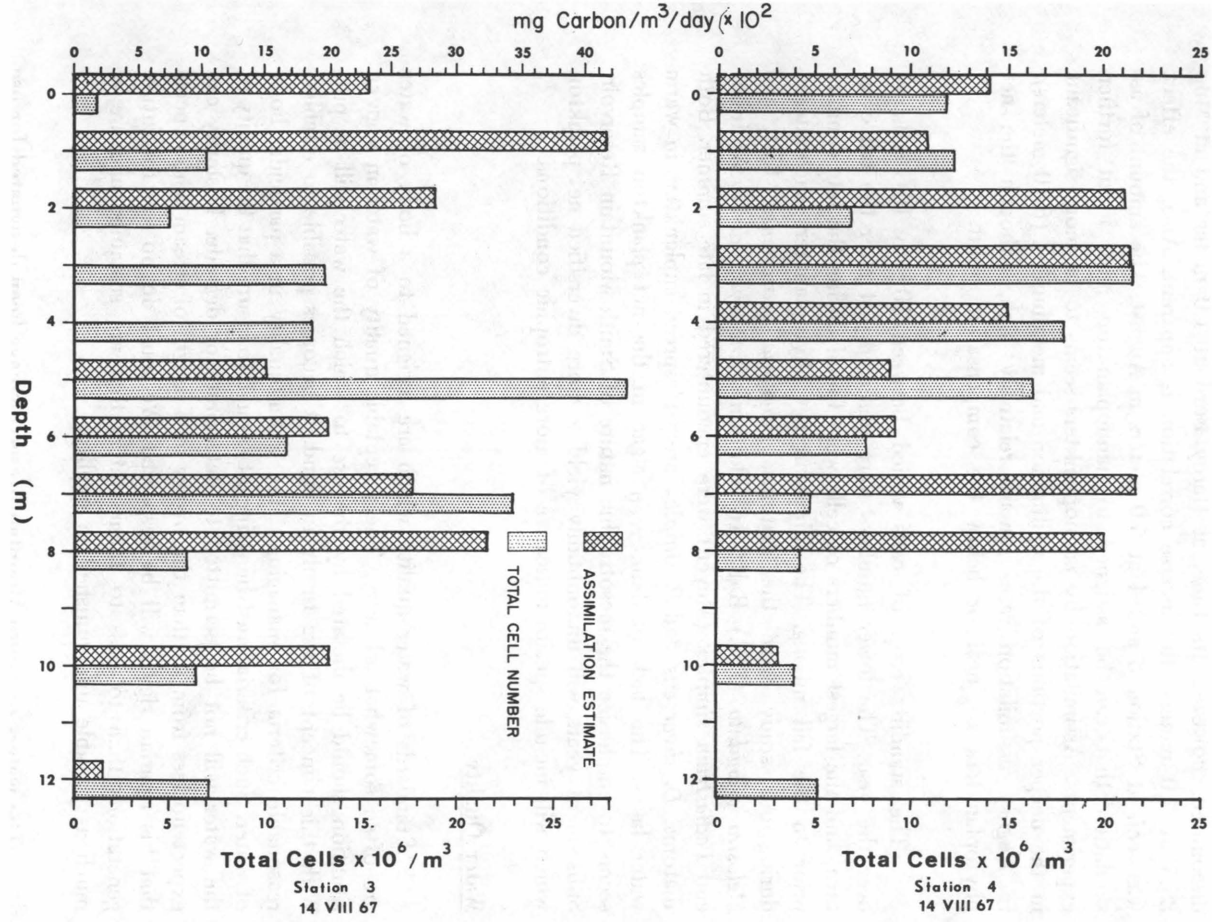


Figure 7. Histograms of the relationship between primary productivity estimates and total net phytoplankton cell numbers, 20 June and 14 August 1967.

does not appear to be any significant light inhibition at the surface in the June or August experiments. The light inhibition factor cannot be completely discounted, however. In June, at Hardy Ford at 1.0 meter and at Mile 35.5 at 2.0 meters, the inverse correlation is apparent. Also, the effect was seen at Station 3 and 4 at 5.0 meters in August. The amount of assimilation that can be assigned to nannoplankton must await further experiments. Assimilation by nannoplankters seems to be more significant in the deeper portions of the epilimnion and metalimnion (6-10 meters). In August, assimilation rates remain relatively high, although the net phytoplankters are near or below the compensation point.

The standing crop of cells varied between 10^4 to 10^7 cells/m^3 over the year. The lower numbers were observed just after the fall overturn, and the largest numbers of cells were found during the late summer prior to the fall mixing. The dominant net phytoplankters encountered during our study were the diatoms, *Fragilaria crotonensis* Kitt. and *Melosira granulata* (Ehr.) Ralfs. In addition, *Dinobryon divergens* Inhof and *Pediastrum simplex* (Meyen) were encountered in late summer. Both diatoms, *D. divergens* and *P. simplex* are widespread euplankters in warm water lakes. The lack of blue-green algae in the net plankton samples seems to emphasize the mesotrophic nature of Smith Mountain Reservoir. Subsequent years will undoubtably yield a more diversified net plankton which will include species indicative of more eutrophic conditions.

Water Quality

Standards of water quality which are assigned to a body of water are often somewhat arbitrary. The acceptable quality of water in a given situation should be dictated by the *use* to which the water will be put. With this concept of *use* firmly in mind, it becomes possible to establish reasonable criteria for managing the water quality in a particular body of water. Such criteria must be stringent enough to insure that the quality of the water will not be permitted to deteriorate or degrade. Posterity can expect no less from us than the owner of a length of stream who expects that his riparian rights will be respected. We must do no less for future generations than to pass to them waters that are sustained and are as much as possible undiminished in quality.

The waters of Smith Mountain Reservoir have been designated for use in recreation, warm-water fishing, and agriculture by the Virignia State Water Control Board. With this designation, the indices of water quality are less rigid than for other bodies of water, such as waters to be used for drinking, etc. The following water quality standards have been recommended for Smith Mountain Reservoir:

Temperature	Not to exceed 95° F, unless caused by natural conditions.
pH	6.5 to 9.0
Dissolved oxygen	Not less than 4.0 ppm at anytime.
Organisms of the coliform group	Not to exceed 2400/100 ml as a monthly average value (either MPN or MF counts); nor to exceed this number in more than 20% of the samples examined during any month. The preceding values shall not be applicable during or immediately following periods of rainfall.

These standards are less restrictive than the criteria for mandatory and desirable factors that have been advanced by the National Technical Advisory Committee to the Secretary of the Interior (Water Quality Criteria, 1968). The Committee recommended that fecal coliforms should be used rather than "organisms of the coliform group." Use of fecal coliforms as an indicator will provide a more precise evaluation of a water's quality. Since much of Smith Mountain Reservoir is utilized to a great extent for primary contact recreation, it behooves us to establish more restrictive standards as far as the coliform group is concerned. We advocate adopting the use of fecal coliforms as indicator organisms and that their content should not exceed 400/100 ml for any 30 day period. This is a little less restrictive than the Advisory Committee's recommendation (p. 4, 12), but will provide for safer recreation use of the reservoir.

The recommended temperatures and pH ranges were not exceeded during our sampling period. Since dissolved oxygen concentrations were depleted and eventually exhausted in the spring and summer in the bottom waters of the upper Roanoke River arm of the reservoir, we decided to investigate that area of the reservoir in terms of the presences of total coliform organisms. Our sampling was not done on a regular basis. Even with only sporatic sampling, the effect of municipal effluents on the reservoir was evident (Table 22). The effects of these effluents upon primary productivity has been pointed out above. It should also be pointed out that the effects of runoff in the Roanoke-Salem area on the total coliform counts in Smith Mountain Lake take place from 3-5 days after the rain. Such a time lag can hardly be construed as being exempt from the period "during and immediately following rainfall" as given in the indices cited above.

All of the assays made during this study were within the limits recommended by the State Water Control Board. High coliform counts were evident in the upper end of the reservoir (Hardy Ford) even after chlorination procedures were adopted by the Roanoke treatment plant in February, 1968. The counts decreased going toward Smith Mountain dam. An exception is the 29 August 1967 sample which was made four days after a heavy rainfall in the Roanoke area. Influence of the runoff is apparent at Hardy Ford (Mile 40 from dam) and Hale Ford (Mile 20 from dam). Effects of the runoff seem to subside rapidly, but this seems to be coupled to the impoundment's ability to assimilate quantities of nutrients in its hypolimnion. In any case, the Hardy Ford area was consistently higher in coliform counts.

Although it is self-evident that the quality of water in the reservoir near the dam is going to reflect the quality of water that is recycled during pumping, a surprising fact emerged from our sampling. This fact was the relatively high total coliform counts obtained near the dam in the summer and fall. It had been anticipated that the recycling process would reduce the total coliform counts in the dam area. It seems that the pump-back operation does account for these increased coliform counts. During pump back, water from the mouth of the Pigg River which enters the Leesville reservoir near Toler's Bridge just below Smith Mountain dam (see Fig. 1) is drawn back into the tail race area and is recycled with the Leesville reservoir water.

The Pigg River receives untreated sewage effluents from a number of small municipalities along its course. Our sampling showed coliform counts from 300 to more than 1600/100 ml. It appears that the river's contribution to the quantity of recycled water is responsible to a large extent for the increased coliform counts. The low water quality of the Pigg River should be corrected soon. A sewage treatment plant is being installed at Rocky Mount, Virginia, and arrangements are being made for treatment of effluents at other points on the Pigg. These modifications of the present system should improve the Pigg River water and bring about changes in the water of the lower reaches of Smith Mountain Reservoir.

TABLE 21. mg Carbon assimilated per m^3 per day at various depths at Station 4 (Smith Mountain Dam), Smith Mountain Reservoir.

	1966				1967
Depth m	May 7	Jul 2	Aug 30	Nov 26	Aug 14
0	9.8	24.3	38.8	19.5	13.9
1	19.7	42.9	34.6	20.2	10.8
2	17.6	26.7	41.4	18.0	21.2
3	29.8	38.0	39.2	3.7	21.4
4	25.5	62.2	40.7	4.8	14.9
5	17.1	44.9	28.4	2.1	14.0
6	11.8	30.7	16.0	0.0	9.2
7	19.2	9.8	3.5	0.4	21.7
8	5.0	6.0	1.8	0.0	19.8
9	1.7	1.5	0.0	0.0	----
10	0.7	1.0	0.0	0.0	3.0
11	0.7	0.2	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0
TOTAL	158.6	288.2	244.4	68.7	149.9

(mg C/m^2/day)

TABLE 22. Total coliform MPN counts in the Smith Mountain Reservoir, testing at 37°C for 48 hours.

	1967						1968		
	Apr 8	Aug 16	Aug 29	Sep 4	Sep 17	Nov 8	Jan 17	Feb 29	Jun 4
Hardy Ford									
Surface	1100	240	>1600	34	542		5400	27	> 16,000
5 m	----	----	>1600	>1600	1600		>1600	240	9,180
10 m	1100	542	>1600	1600	920			79	3,480
Hales Ford									
Surface	0	23	>1600	11	2		>1600		
5 m	0	----	>1600	27	14		0		
10 m	35	79	-----	33	348		2		
20 m	75	14	-----	-----	----		0		
30 m			>1600	542	29				
Confluence of Roanoke River and Blackwater River									
Surface	36	23	920			2			
10 m	23	172	22			0			
25 m	120	1160	25			8			
Smith Mountain Dam									
Surface	43	348	33			2			
10 m	64	920	17			12			
25 m	120	221	-----						
37 m			1600			542			

CONCLUSIONS

Smith Mountain Reservoir, Virginia is the eighth pumped-storage hydrogeneration system in the United States. Since the impoundment reached its operating capacity in February, 1965, it has developed some of the limnological attributes of a mesotrophic lake. Further developments suggest the impoundment is rapidly developing the characteristics of older, eutrophic, main-stream reservoirs. This change is occurring despite the recycling of large quantities of water during pump-storage operation.

The thermal regimen of the impoundment indicates that the body of water behaves as a warm monomictic lake. A relatively shallow (5-8m) epilimnion forms during stratification. The metalimnion is nearer the surface in the proximity of the dam during pump-back. The anticipated beneficial effects of the recycling process appear to be limited. Seiche action begun by recycling seems to increase carbon assimilation rates in the vicinity of the dam, and this increase appears to be due to eddy diffusion of nutrients across the metalimnion. Seiche activity is restricted by the impoundment's basin morphometry, but the influence of the pump-back seiche can be detected up to 6.5 miles above the dam.

During summer stratification, hypolimnetic oxygen depletion was observed. In the lower parts of the impoundment, anaerobic conditions in the hypolimnion were not reached although dissolved oxygen concentrations were severely reduced. In the shallower upper reaches of the impoundment, anaerobic conditions developed by late spring. The highest concentrations of dissolved oxygen were encountered in spring and early summer in the epilimnion. These oxygen concentrations (90-127% saturation) paralleled photosynthetic activity which was estimated as inorganic carbon fixation by the Carbon-14 method.

Primary productivity studies support the idea that carbon assimilation rates are relatively low in new impoundments. Rates observed in Smith Mountain Reservoir compare favorably with estimates made in certain mesotrophic lakes. Differences in the carbon assimilation rates on the Roanoke and Blackwater arms of the reservoir reflect the enrichment of the Roanoke arm by industrial and domestic effluents. Estimates from the Hardy Ford area indicate that the impoundment will approach hyper-eutrophic conditions in its upper reaches in the next decade.

High carbon assimilation rates were not necessarily correlated with high standing crops of net phytoplankton. In fact, some data supports

Findenegg's observation that there is an inverse relationship between assimilation rates and total phytoplankton cells. While physical factors appeared to prevail in controlling rates of assimilation, nutrient depletion and metabolites may also influence carbon assimilation. Correlation coefficients illustrate a significant (1% level) positive association between cell populations and carbon assimilation rates. In nature, this correlation will depend upon the interaction between the cells and the limnetic environment at any given period of time.

Total coliform counts made at various times in the reservoir also emphasize the quantities of effluents that enrich the upper portions of the impoundment. These counts also point out the self-evident fact that water quality improvement in pump-storage reservoirs depends upon the quality of the water which is recycled. If pump-storage types of impoundments are to be considered for enhancing water quality in a situation, detailed observations on the quality of water to be utilized must be carried out.

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